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Progress In Electromagnetics Research Symposium

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PIERS 1998

Progress in Electromagnetics Research Symposium
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FRIDAY, JULY 17, PM

General Chairman's Welcome

After Cambridge, (USA, 1989 and 1991), Pasadena (USA, 1993), Noordwijk (The Netherlands, 1994), Seattle (USA, 1995), Innsbruck (Austria, 1996), Hong Kong (January 1997) and Cambridge (USA, July 1997), the 1998 Progress in Electromagnetics Research Symposium will be organized in France from 13 July through 17 July 1998. We are honored to host PIERS 1998 in Nantes.

On behalf of the International and National Organizing Committees of PIERS'1998 I would like to welcome you to the ninth PIERS, the third PIERS held in Europe. For the first time a 12-day conferences on Electromagnetics will be organized in European Countries with the International Workshop on Finite Elements for Microwave Engineering, 10-1 July 1998, in Poitiers, France, PIERS'1998, 13 to 17 July in Nantes, France and PIERS Workshop on Advances in Radar Methods, 20-22 July, Baveno, Italy. Several workshops have been organized and I would like to draw your attention in particular to the 4th International Workshop on Radar Polarimetry and the Workshop on Complex Media and Measurement Techniques included in PIERS'1998. Two one-day workshops presented by invited expertshave been organized on important topics.

PIERS'1998 offers a broad spectrum of sessions in various fields of electromagnetic theory and its new exciting applications. It encourages interaction between different fields and reports most recent advances and progress in electromagnetics. More then 1000 papers have been received from 46 countries in the world. More than 600 persons are, already, pre-enregistered. The Technical Program Committee, under the chairmanship of Dr. Thuy Le Toan, together with more than 100 sessions organizers, has done an outstanding job of arrangin sessions covering all areas of electromagnetic research. Most of these sessions are organized by distinguished experts in the field with invited specialists reporting on their most recent work. As far as possible, the sessions have been arranged in homogeneous thematic topics to assist you, the conference participants in your individual selection.

We have also scheduled several social events for relaxation and enjoyment during the week. The Mont Saint Michel tour, the walking tour of Nantes, the guided tour of graves vineyards and the Chateaux de la Loire tour, the Loire valley tour are wonderful events not to be missed by you and your companions. A gala dinner is organized on Wednesday, 15 July in the "Chateau de la Poterie" after a lovely river on the Erdre river.

PIERS'1998 could not have been organized without the sustained efforts of the Session Organizers. I am very grateful for their valuable contribution to the symposium. I would like to take this opportunity to thank the members of the Technical Program Committee and the National and International Steering Committees, chaired by Dr. Thuy Le Toan and Pr. Joseph Saillard for their excellent work in preparing and coordinating the program and in organizing the PIERS'1998 web site. I would also like to thank the members of the Organizing Committee who readily accepted the considerable workload in administration and management of the symposium and in the organization of all the social events. Without the financial support of local, national and international agencies we could not organized in PIERS'1998 Symposium in France at such low registration rates. This financial support has also allowed us to invite more than 10 specialists in electromagnetics from the former SOVIET union to share their expertise. We wish to thanks all these agencies for their contribution to the success of the Symposium.

I hope you will find this symposium to be great scientific interest and benefit as well as an enjoyable social occasion to meet friends and colleagues and to discover the beauty of this part of France.
Thank you for joining us.

A. PRIOU
PIERS'1998 General Chairman

Session A06
Wednesday, July 15, PM 13:40-16:00
Room L
Asymptotic High Frequency Techniques

Organiser : F. Molinet

Chairs : M. Idemen, F. Molinet

An inverse Mixed Boundary-Value Problem Connected with One-Dimensional Profile Inversion of a Slab and Half-Space Bounded by an n-Part Impedance Boundary

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An inverse mixed boundary-value problem whose aim is to determine the constitutive electromagnetic parameters of a slab and half-space bounded by an n-part impedance plane is studied. It is assumed that the constitutive parameters are functions of the altitude x_3 while the known impedance of the boundary, say $x_3 = 0$, depends only on x_1 (see the figure below). Then, by using the data obtained by measurements of the electric field on a straight-line parallel to the x_1 -axis, one reduces the problem to the solution of two functional equations. By using an ad-hoc représentation, the first functional equation is transformed into a generalized Wiener-Hopf problem which involves n unknown functions having certain analytical properties. To solve this latter which can not be solved exactly when $n \geq 3$, one establishes a new method permitting one to obtain the asymptotic expressions valid when the wave-length is chosen sufficiently small as compared to the widths of the impedance strips. The second functional equation whose kernel involves the solution to the first one constitutes an inherently ill-posed problem. To reduce the effect of the ill-posedness, a regulized solution in the sense of Tikhonov is found. To show the applicability as well as the accuracy of the method, some illustrative example are considered.

The method used to solve the first functional equation can also be used to solve the direct n-part boundary-value problems which hace not yet been cinsidered in the open literature.

Floquet-Wave and Guided-Wave Diffraction for a finite Phases Array on a Grounded Dielectric Slab

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Several studies [1]-[5] have recently been carried out on frequency- and time-domain scattering from finite periodic or quasi-periodic structures in free-space and on an infinite dielectric slab. These studies have demonstrated the effectiveness and physical insight gained when describing the scattering phenomena in terms of truncated Floquet waves (FWs) and/or Floquet-modulated other wave types. In particular, by using the Poisson summation formula, the Green's function of a finite array is represented collectively as the radiation from a superposition of continuous truncated FW distributions on the aperture of the array. Since the FW series exhibits excellent convergence properties when the observation point is located away from the array surface, the above representation is found more efficient than the direct summation of the spatial contributions from each element of the array, especially when each FW aperture distribution is treated asymptotically.

In this paper, the high-frequency diffraction phenomena occurring at the edges of a finite array of a wire grating excited by a plane wave are investigated. The FW-diffracted rays and the excitation of guided waves (GWs) at the array truncation are described. Furthermore, the diffraction mechanisms at a slab truncation of all type of waves excited at the array edge are discussed, with emphasis to the transition conditions from homogeneous to evanescent FWs and to the phase locking mechanism between FWs and GWs.

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Surface Wave Fields : High Frequency Representation and Characteristics in a Multilayered or Periodic Plane Structure and in a Multilayered Cylindrical Structure

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Surface waves are defined as waves which travel along surfaces with their fields confined to the neighbourhood of the surface. These waves occur in electromagnetics on corrugated metal surfaces, on metal surfaces with periodic structures and on dielectric or magnetic coated surfaces. These waves can be also met in acoustics.

In the first part of the paper, we discuss a geometrical theory developed for the analysis of electromagnetic surface wave excitation and propagation on a multilayered or periodic plane structure. This ray representation can be applied to acoustics. We characterize the surface wave by a real or complex propagation constant $k=\omega/c$, ω is the angular frequency, c is the real or complex phase velocity along the surface. We determine k or c from a pole search of the reflection coefficient for a specified material profile. We apply these asymptotic theory to the specific case of a structure comprising a biperiodic grating of metallic plates between stacks of dielectric media upon a perfectly conducting plane. We give some new results about the excitation of a surface wave on this structure. This surface wave permits the absorption of the incident wave. We determine the damping of the wave along its propagation and the manner how such waves propagate. We can construct a geometrical theory for these surface waves analogous to geometrical theory of diffraction. This ray representation provides an understanding of generated surface waves propagating on the surface of a multilayered plane structure. We discuss the different applications of these surface waves. In conclusion we give the expression of the so-called lateral wave and its physical meaning in the analysis of the reflected wave for a multilayered plane structure.

The second part of the paper contains the asymptotic analysis of the surface wave field for a multilayer cylinder. We analyze the acoustic and electromagnetic cases. The excitation is limited to that of a plane wave and the observation point is separated from the cylinder by a distance which is large compared with wavelength. The oblique and normal incidences are considered. In the scattering of electromagnetic waves from multilayered structures resonances appear in the scattering amplitude. These resonances are related to poles of the Green's function. The location of these poles defines the varieties of surface wave phenomena which can be observed on the multilayered structure. Asymptotics leads to ray interpretations for the total field in terms of incident and reflected waves augmented by creeping waves, leaky waves and trapped waves. We give the coupling coefficients between the different surface waves and the bulk wave at the points of ray attachment and shedding, the geometrical description of the surface waves on the structure and the spreading factor. In the case of oblique incidence, we do not separate TM and TE polarizations with the local Frenet triad, used for perfectly conducting surface in the GTD-type formulation. In this case of oblique incidence, we show that the wave trajectories verify the laws of ray optics when these laws are extended to anisotropic surface rays. A refraction effect specific to a given pole occurs at the points of attachment and detachment of the surface wave ray. In this part of the paper we give an asymptotic representation for creeping, leaky waves which can extend GTD representation to multilayered material cylindrical surfaces.

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- G. Berginc, *Surface wave fields in the presence of a complex curved structure: high frequency model*, Proceedings, PIERS 1995 Seattle, p 497

Some new Results on Creeping rays

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Creeping rays propagate, and get attenuated, near the surface of convex bodies. They can be initiated by a plane wave, at the light shadow separatrix, or by a source near the surface of the body. The traditional approach to study the creeping rays, is to use some canonical problems, generally the sphere and the cylinder, and to generalize the results to an arbitrary convex body. This method does not however permit to take into account such effects as variation of curvature, or variable impedance. To study this kind of effects, we use the boundary-layer method as explained for example in [1]. The principle of the method is to represent the creeping wave near the surface of the body by an ansatz, depending on some functions. This ansatz has to satisfy the Maxwell equations, the boundary conditions of the body, and some form of radiation conditions. By imposing these requirements, these functions, and hence, the ansatz, is determined. The computations are performed in a geodesic coordinate system on the arbitrary convex body, so that the effect of the geometry of the body is straightforwardly taken into account. We have applied this technique to various problems of creeping waves, as detailed in [2,3] for example.

In this paper, we focus on the effect of transverse curvature on the propagation of creeping rays. When the transverse curvature c is of the same order of magnitude as the curvature $1/\rho$ of the creeping ray, a correction of the propagation constant of order $c\rho^{1/3}\, k^{-2/3}$ appears, which depends on the impedance of the body. The effect is especially important for the case of a creeping ray with magnetic field parallel to the surface of a perfectly conducting body, in which case our results are the same as those given in [4]. However, when $c\rho^{1/3}$ increases and becomes of order $k^{-2/3}$, the propagation constant is modified in the principal order, and goes to 0 when $c\rho^{1/3}$ becomes infinite.

We present the method of computation and some analytical and numerical results for this propagation constant.

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[4] M. Voltmer, Ph. D. Thesis, Ohio state university, 1971

Asymptotic Currents Method

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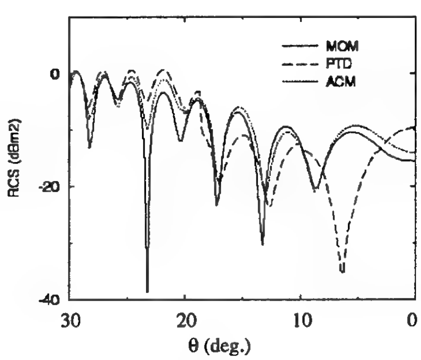
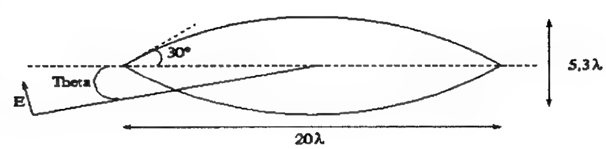
An Asymptotic Currents Method (ACM) is based on an asymptotic approximation of the surface fields, and on an evaluation of the scattered fields by the STRATTON-CHU integrals. The most famous and simplest asymptotic currents method is the Physical Theory of Diffraction (PTD). The PTD considers the non-uniform induced edge currents in addition to the uniform induced surface currents of Physical Optics. However, the shadowed regions are not taken into account, and the non-uniform currents do not allow to precisely represent multiple edge diffractions or corner effects.

The alternative method presented in this paper consists in using the Uniform Theory of Diffraction (UTD) to compute the surface fields, and then the uniform surface currents on all surfaces (shadowed regions, edge vicinities, illuminated regions, ...). A ray tracing method, developped in a DASSAULT code called SPECTRE, performs the computation of the three dimensionnal geometrical ray sheets (2). Different kinds of rays are been considered, including :

- creeping rays launched from the shadow boundary,
- diffracted and creeping rays launched from an edge,
- sequences of creeping-diffracted-creeping rays coupling the two previous interactions.

Then, the surface fields are evaluated using formulations developped by MOTHESIM, and the scattered field are expressed in terms of surface integration of the currents. Numerical illustrations have been computed using canonical bodies and are compared with elements method. The new formulation was first tested numerically on a prolate spheroid to compare the asymptotic currents in the shadowed region with the reference solution given by the three dimensionnal boundary element method. For the second test, the target is an ogival cylinder providing multiple diffractions between wedges on convex surfaces :





Monostatic cross section, F=10GHz, θθpolarisation.

In all cases, we obtain a very good agreement with the integral method. The comparisons show that our method improves the usually used asymptotic methods (UTD, PTD).

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Creeping Waves and Whispering Gallery Modes on Convex and Concave Surfaces Coated with a Uniform Layer of Biisotropic or Bianisoptropic Material

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The analysis of electromagnetic interactions with metallic objects covered with special materials either biisotropic with chiral properties or bianisotropic [1] are generally limited to the reflection and refraction of waves. However, other diffraction pheneomena which cannot be describe by geometrical optics appear in the form of guided waves propagating along the surface and shedding energy in the medium outside the coating, either directly or by diffraction on a singularity of the geometry on a junction of different materials.

The method used to investigate this problem is the Watson Transformation which has been extended to anisotropic material in [2] and which we have further extended to biiosotropic and bianisotropic materials.

In the first part of the paper we analyse the variation with respect to the thickness of the layer and its electromagnetic properties, of the real and imaginary parts of the propagation constants of creeping waves and whispering galery modes on a convex, respectively concave coated circular cylinder at normal incidence. The case of anisotropic material with axes of anisotropic respectively parallel and perpendicular to the axis of th cylinder is considered first. Then the investigation on the propagtion constants is extended to biisotropic chiral material. The characteristic equation is established and solved and the sensitivity of the propagation constants to the chirality parameter is analysed. It is shown that the effect of chirality on the attenuation of whispering galery modes is small for existing materials [3].

The theoretical analysis is finally generalized to bianosotropic materials. Some numerical results on the propagation constants on a cylinder coated with a uniform layer of bianosotropic materials having chiral properties are also given.

In the second part, asymptotic expressions of the field on the surface of the croating due to a line source are presented. In the case of a concave coated surface a description by a canonical integral coupled with geometrical optics [4] has been adopted.

Numerical results are presented for different kinds of materials considered in the first part.

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Session A07
Wednesday, July 15, PM 16:00-20:00
Room 300
Rough Surface Scattering, Methods and Applications

Organisers : G. Berginc, Y. Beniguel
Chairs : G. Berginc, Y. Beniguel

Inverse Scattering Problem for Rough Surface Scattering

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Let us consider inverse scattering problem for the case of radiation interacting with rough surface. In the simplest case it can be formulated as follows. Let us consider a surface representing infinite plane which includes a piece of roughness with compact support. In this work we consider 2-D case and assume a surface satisfying Neumann boundary condition. Let a point source of radiation is located at infinity and near the surface, so the incident wave front represents plane wave propagating along the surface. Let us assume, that the source function in time domain represents delta-impulse. When radiation reaches inhomogeneous part of the surface, scattered waves appear which propagates along the surface in the backward direction. This scattered field is recorded as a function of time in the location of the source. The problem is to retrieve the shape of the roughness based on the measured back scattered signal.

This inverse problem is very well studied with respect to wave (Shrodinger) equation with volume inhomogeneities, especially in 1-D. In this case solution can be reduced to the linear Gelfand-Levitan-Marchenko (GLM) equation (in the absence of discreet spectrum). The other approach is related to so-called layer-stripping algorithm, which directly exploits casuality principle.

In this work similar layer-stripping algorithm is developed regarding formulated above inverse scattering problem associated with rough surface scattering. To evolve solution in space one needs to solve at a corresponding moment of time a linear integral equation which includes information about roughness inferred at the previous steps. Thus, in contrast to GLM equation this algorithm represents in fact a non-linear procedure.

This approach is not related to some approximate method of calculation of scattering, and is in principle exact. Some particular cases are considered, and appropriate numerical algorithm for surface shape reconstruction is presented.

Stochastic Integral Equation for Rough Surface Scattering - Rayleigh Approximation -

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At PIERS'97 the present authors reported that a new stochastic integral equations for rough surface scattering can be derived, which is of the first kind and the second kind integral equation for an infinite rough surface based on the stochastic Floquet theorem, that the simplest solution of the second kind equation automatically gives the Kirchhoff solution and that the first iterated solution gives the «doulbe» Kirchhoff solution. The present paper gives an attempt to obtain a stochastic solution for the first kind equation, assuming the rough surface to be a homogeneous Gaussian random field. Depending on the different representations for the propagator along the surface, we have two forms for the first kind integral equation, which are valid for arbitrary roughness. It is however shown that one form of the equation is usually difficult to solve but takes on a easily tractable form in the Rayleigh approximation, and that the other form is tractable in the case of the non-Rayleigh representation of the wave field. The present paper gives a method to solve such a stochastic integral equation based on the small slope concept using the Wiener's functional calculus, and obtain the stochastic distributed source function finally to calculate the angular scattering distribution. Our solution by some approximation is reduced to the ordinary solution of the small slope approximation, and the simplest solution again leads to the Kirchhoff solution for an infinite random surface. The solution due to the present method automatically involves the nonlocal expansion of the small slope approximation.

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Comparison of Scattering from Gaussian and Non-Gaussian Rough Surface Having the Same Spectrum

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We develop a mathematical model of a statistically homogeneous rough surface that satisfies the following conditions :

1. It has a given (anisotropic) spectrum.
2. It has a given (non-Gaussian) joint probability distribution function (PDF) of two principal slopes in any fixed point.
3. It allows to obtain the joint probability distribution (characteristic function) for arbitrary number N of surface elevation differences $z(\mathbf{r}') - z(\mathbf{r}'')$ in an explicit form.
4. It allows to find any mean scattering cross-sections, used in any theory of wave scattering from rough surface, in an explicit analytical form.
5. To describe the non-Gaussian PDF we use decomposition of the non-Gaussian PDF in the sum of Gaussian PDF having different positions and different correlation matrixes instead of the cumulant expansion approach.

This method for describing the non-Gaussian distributions is rather simple and may be used in a wide class of statistical problems.

The most of statistical models of non-Gaussian random surfaces describe the PDF of the elevations or the joint PDF of elevations and slopes at the same single point of the surface. This is enough for describing the scattering of waves only in the geometrical optics approximation (e.g., altimetry). For describing the scattering and diffraction of waves by random surfaces in a more general case we need at least two-point PDF (for the Kirchhoff approximation) or three- and four-point PDF (for the small-slope and tilt-invariant approximations) [1]. The method described in the paper [2] allows to find the joint PDF of elevations of an arbitrary order, but it is too complicated for real computations. The method presented in this paper is much simpler.

Using this model, we calculated the scattering from a perfectly reflecting rough surface, having non-Gaussian PDF of slopes and anisotropic spectrum (they correspond to experimental data for wind-driven waves on the water surface). In the Kirchhoff approximation we obtained a significant difference between Gaussian and non-Gaussian cases with the same spectrum.

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Model of VHF Radio Wave Scattering by the Sea Surface at Low Grazing Angles

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The two main features were taken into account in theoretical investigation of the processes of VHF radio wave backscattering by the rough sea surface at low grazing angles:

a) the concave form of the most part of the undulating sea surface (the area with the positive curvature exceeds essentially the part with the negative one);
b) distortion of the incident wave by diffraction effects at the sea wave crests preceding to scattering by small-scale roughness.

Backscattering of electromagnetic waves from cylindrical impedance concave statistically rough surface is studied theoretically by the small perturbation method for vertical (TM) and horizontal (TE) polarization. It is assumed that a radius of curvature of a cylinder significantly exceeds radiation wave length. We use the Fock representation for the concave impedance cylinder Green function in terms of series of "normal" modes. The grazing angles of the first modes (whispering gallery waves) are assumed to be mush smaller than the Brewster angle. As a result, the TM modes attenuate faster than TE ones. The decrements of attenuation can be calculated analytically in the WKB approximation. It appears that for low grazing angles the decrement of attenuation does not depend on mode number, and is a function of the radius of a cylinder and the value of impedance only. Due to the difference in attenuation decrements between TE and TM waves, back scattered signal for TE incident wave can be comparable or even bigger than backscattered signal for TM case.

The incident wave diffraction caused by sea wave crests was considered using the simplest models of the crest shape. In all cases the diffracted field increases the strength of the TE field and decreases TM one. These results can be used for interpretation of anomalous behavior of polarization ratio for back scattered electromagnetic waves of centimeter range from a rough sea surface at low grazing angles.

Extension of Small Slope Approximation Method for 3D Scattering Cross Section Calculation of a Rough Convex Object

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The analysis presented focuses on the calculation of the 3D scattering cross section of rough canonical objects. The irregularities are randomly distributed throughout the surface. They are characterized by two parameters: their height standard deviation and their autocorrelation length. Particular attention will be paid to the case when the autocorrelation length to standard deviation ratio, defined as the surface slope is low. The cross section may be defined by an area intercepting that amount of power which, if scattered uniformly in all directions would produce a scattered power density at the receiver equal to that reflected by the target. We shall discuss the computation method we propose. The scattering cross section of the surface is calculated by the small slope approximation (SSA) method [1]. Second order terms in SSA approximation have been implemented in order to obtain accurate results for a large range of slopes. It has been shown that SSA applies not only to small slope profiles but also to significant values of this slope including cases where the Kirchhoff approximation is usually used. In particular it allows to exhibit the backscattering phenomenon enhancement [2] which can be explained as a consequence of double interactions. We show that the actual backscattering phenomenon enhancement involved is not underestimated by the 2nd order small slope approximation.

Considering the scattering cross section (SCS) calculation of rough convex objects, the surface is divided into patches. It can be shown that the edges of these patches do not bring additional contribution to the scattered field [3]. The size of the patches has to be greater than a few coherence lengths. The case of non perfectly conducting objects can be studied as well. We show that additional terms are involved in the algorithm in this case.

SCS calculations have been performed on canonical structures. Discrepancies between results obtained with different techniques including first and 2nd order SSA and Kirchhoff approximation will be presented with respect to the surface slope. We analyze the influence of the different parameters (geometrical parameters of the object, surface parameters, electromagnetic parameters) on the amplitude of the scattering cross section.

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Direct Monte Carlo Simulation of the Ocean Surface

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Modeling the electromagnetic wave scattering on the random ocean surfaces requires a mathematical model for a surface with statistical properties satisfied the experimental data [1]. The major statistical characteristics are surface spectrum, probability distribution functions (PDF) of elevations and slopes.

For numerical simulation of the scattering by rough surfaces we need to construct ergodic random surfaces, i.e., such random surfaces that each its realization obeys the above mentioned properties if we replace the statistical averaging by the averaging over the position of the point at the surface.

In this paper I present a new numerical method to model the non-Gaussian random ocean surfaces. Proposed method allows to generate a random surface satisfying the several statistical characteristics simultaneously.

Based on this method I develop a numerical model which simulates a random surface with given experimental PDF of elevations and PDF of principal slops. This model can be only used in numerical simulations of rough surface scattering in geometrical optics approximation. Currently, it is applied for modeling the lidar images of underwater objects.

Developed model can be easily modified to account for other experimental statistical characteristics, such as surface spectrum. It implies that the model are suitable for a wide class of problems.

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Scattering by Two-dimensional Dielectric Random Rough Surfaces : Numerical Simulations and Measurements at Various Incidence Angles

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The problem of electromagnetic wave scattering from random rough surfaces has applications in many fields of physics. In particular, in optics, there is a great interest for the calculation of the scattering properties of a realistic randomly rough surface, which implies to solve the electromagnetic problem in a three-dimensional geometry (two-dimensional surfaces). Many methods, whether analytical like the Kirchhoff approximation or the perburbation methods, or numerical like Monte-Carlo simulations, have been applied to one-dimensional perfectly conducting or dielectric surfaces. Recently some numerical calculations based on integral methods gave results for the electromagnetic scattering by two-dimensional randomly rough surfaces [1, 2].

New results are given for the scattering of optical waves by a two-dimensional randomly rough dielectric surface. These are numerical simulations carried out with a new approximated method based on the use of plane-wave expansions and the Rayleigh grating model [3], as well as measurements achieved with a fully automated laser scatterometer [4]. The numerical method lies on the Rayleigh hypothesis. It was shown that the random surface could be represented by a random grating by comparisons with integral calculations on a finite random surface length [4]. In this framework the reflected field and the field transmitted through the interface are expressed as plane-wave expansions decomposed on a local basis. This decomposition separates s- and p-polarisation components of the fields and reduces the number of unknown plane-wave amplitudes by realizing a projection of a three-dimensional problem onto a two-dimensional space. Then these expressions are injected in the boundary conditions coming directly from Maxwell equations showing the transmission of the electric and the magnetic field through the interface. To solve the problem the plane-wave expansions are truncated and the boundary equations are projected on a Fourier basis. This operation leads to a matricial system where the matrix coefficients can be straightforwardly calculated by using few Discrete Fast Fourier Transforms. Numerical properties of this three-dimensional Rayleigh-Fourier Solution are discussed. Computation time performances on the IBM SP/2 of CEA/CESTA are given. Convergence properties of the solution are studied by means of the calculation of the energy conservation. Different results are presented that are compared with existing references or show the influence of the angle of incidence. Also a confrontation to experimental results obtained in the infra-red is examined.

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Study of Slops Variances of the Sea Surface

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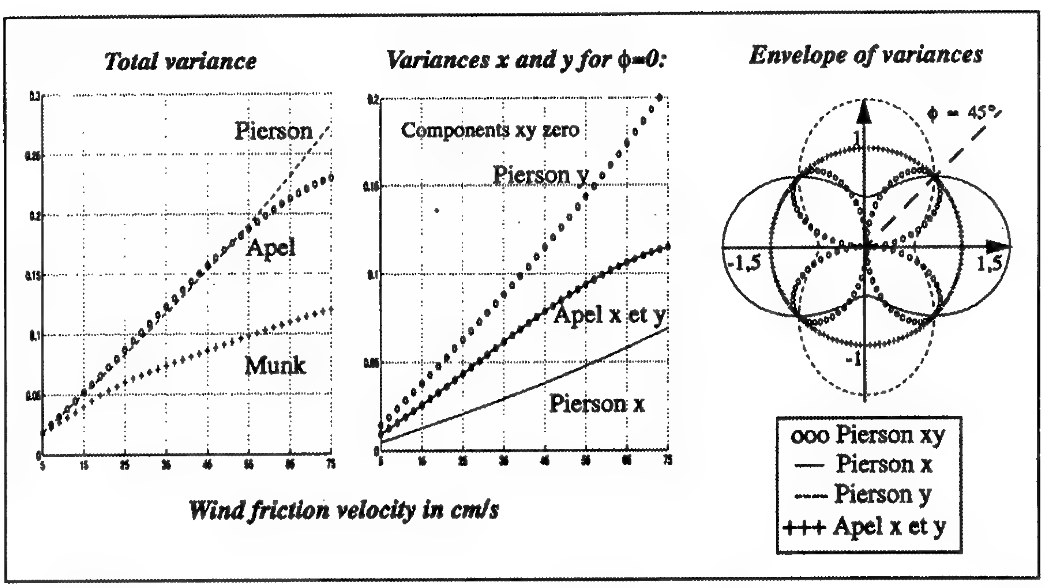
The ocean presents an uncoordinated aspect, so the fluctuations of the sea are represented by a four dimension random variable : one temporal component and the three others spatial. This processus is also supposed ergodic and stationnary. The stationnarity involves that the autocorrelation function is obtained from the spectrum by an inverse Fourier transform. More of that, we suppose that the density probability of the heights is a gaussian, characterized by its variances and its mean values. The linearity of this processus involves a gaussian distribution of the slopes.

In this paper, we present the slopes variances corresponding to the value of autocorrelation function at zero. This information is necessary to determine the scattering from a roughtness surface (Kirchhoff's model and shadowing function). We will compare our results, with those of Cox and Munk obtained from the aerial photographs, for two bidimensional spectral configurations of the sea (Figure 1) : the Apel spectrum is based on recent work (1990) by Donelan, Banner, Jähne and their collaborators ; the Pierson spectrum added of its angular function, was developed in the 1970 years.

The slopes variances of the sea surface will presented, in each configuration, in function of two parameters. The first gives the behaviour as function of wind velocity (figure 2), and the second as function of the observation direction (figure 3). The angular integration is analytic. This characteristic does the originality of our method, whereas the integration which depends on the wave number is numerical.



Experimental and Theoretical Investigation of Coupling between Surface and Subsurface Scattering

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This paper describes the phenomenon of optical scattering by an inhomogeneous 1-D medium under a diffuse reflection at its upper boundary surface. We focus our study at infrared wavelength (5.4 µm) and unpolarized incident radiation. The inhomogeneous medium is composed of small spheroidal dielectric particles in a polymeric resine coated on a metallic substrat. We measure diameters of particles with an Electronic Scanning Microscope. We also verify the non-dispersion in size and the random uniform distribution of particles in the matrix. The statistics of the rough surface are supposed to be gaussian and the roughness parameters are measured with an optical profilmeter ot Atomic Force Microscope.

As we used weak volume fraction, we assumed independent regime for subsurface multiple scattering. Volume scattering is describe by the radiative transfer theory and radiative properties are well predicted by Mie solutions. Numerical solutions of the problem are obtained by coupling the Doubling and Discrete Ordinates Methods [1]. Simulations of surface scattering are based on 3D Rayleigh grating calculations [2]. We assumed no mutual interference between the two phenomena. Under these conditions, the coupling between surface and subsurface scatterings is achieved by introducting rough interface scattering properties into the radiative boundary conditions.

We compared numerical simulations of subsurface, surface and coupled scattering with bidirectional reflectance measurements. For this purpose, three different kinds of media are used which respectively are :

- Inhomogeneous matrix and flat upper boundary,
- Homogeneous matrix and rough upper boundary,
- Inhomogeneous matrix and rough upper boundary.

Influence of coupling effects are investigated and studied for different subsurface scattering regimes by increasing the optical thickness. We change the depth of layered polymer but volume fraction remains un changed. We compare the coupled difuse scattering to the simple addition of surface and volume scatterings. Different surface reoughness parameters and incident radiation have been investigated.

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All-Wave Rough Surface Scattering Theory

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Well-known to us theories on the subject of scattering from statistically routh surfaces were applicable only for small or very great scattering elements of the rough surfaces relative to the wavelength of incident radiation [1]. Below is presented the scattering theory for all relations of the electromagnetic wavelengths to the reflectors' sizes.

The general vectorial theory includes a number of separate theories :

a) Diffraction-statistical theory (DST) of scattering of electromagnetic waves (EMW) by statistically rough surfaces.
b) Statistical theory of scattering of the EMW.
c) Theory of depolarization of EMW.
d) Scattering theory for forest (STF).
e) Scattering theory for sea (STS).

The novelty of the DST is that it fits all relations of the EMW lengths to the reflectors' sizes.

The foundation of the DST is a model: ensemble of independent chaotically placed relectors of certain forms and sizes; and also methods: of Ufimtsev, Keller, Eggimann and etc.. DST made it possible to get simple calculating formulas for the mean value of polarizational scattering matrix elements.

The Non-Gaussian statistical theory uses an ensemble of scatterers' ensembles. As a result it allows us to derive simple formulas to calculate the second moments of polarizational matrix elements and the variation coefficients.

Theory of depolarization of the EMW makes it possible to research the depolarization of EMW scattered by statistically rough surfaces depending on all the physical factors causing the depolarization, each of them alone or all of them combined.

Depolarization theory is formed in the following way.
First the factors that cause depolarization of the scattered EMW are recorded. Those factors are: edge wave, difference of geometric characteristics of reflectors in different directions (non-isotropy), difference in the Fresnel reflection coefficient for the waves polarized horizontally (H) and vertically (V) ; multiple scattering. Then the depolarization coefficient, caused by each of these factors, is calculated.

The solution was demonstrated for one scatterer with a fixed orientation, one scatterer with a changing orientation within a certain sector of angles, an ensemble of scatterers and for an ensemble of scatterers' ensembles.

STF is based on researching the following characteristics: radar cross section (RCS) per unit area of parallel polarized component, RCS per unit area of cross polarized component, mean value of the depolarization coefficient, cross correlation of cross and parallel polarized component, propagation vegetation loss, height of the maximum relecting layer.

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Analysis of Scattering From Fractally Rough Surfaces by Using the T-Matrix Method

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Abstract: In this paper, a time-varying band-limited fractal model is proposed for modeling dynamic evolution of sea surface. A new method for scattering from fractally rough perfectly conducting and dielectric surfaces is formulated with use of the T-matrix analysis and the extended boundary condition method. We expand the field through generalized Floquet modes and the analytical form of the expression of matrix elements is presented in term of the Bessel functions. We obtain analytical closed-form expressions for the scattering amplitudes for both horizontal and vertical polarization of the incident electromagnetic waves. The validity of this method is checked in several ways, such as comparison with approximate method (Kirchhoff and Rayleigh method) and calculation of the energy-balance parameter. We also calculate fractal dimension of the scattering coefficient as function of time using the morphological covering algorithm, and show that the scattering coefficient as function of time is a fractal function with same fractal dimension of sea surface model. Finally, numerical scattering results from fractal surfaces are provided.

Session B05
Wednesday, July 15, PM 13:40-17:00
Room G/H
Microwave Imaging and Dielectric Reconstruction Techniques

Organisers : Ch. Pichot, S. Caorsi

Chairs : Ch. Pichot, S. Caorsi

Born Approximation Diffraction Tomography Revisited

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Diffraction tomography (DT) is the means by which one reconstructs the spatial distribution of some physical parameters of an object from measurements of the scattered field. The measurements are made for more or less dense sets of object orientations (for fixed emitter and receiver) and frequencies of the (band-limited) interrogating (usually plane) wave.

The so-called linearized versions of DT are usually based on the Born or Rytov approximations of the total field within the object. This leads to a particularly simple and attractive (linear) relation between the object function (OF) and the (usually far-) scattered field, making it possible, in principle, to reconstruct the OF in near real time for a sufficiently large set of scattering data.

Considering its wide range of interest, the Born approximation version of DT (i.e., BADT) has been submitted to surprisingly few evaluations of its accuracy and range of applicability. Although the evaluations that have been made usually concern a relatively low-contrast, non-lossy, homogeneous object of simple shape having characteristic overall dimensions that are either comparable to or smaller than the median wavelength (medium to low frequencies) of the interrogating wave, the BADT is in practice actually used at high frequencies, sometimes for medium-to-high contrasts, and for lossy, inhomogeneous objects or arrays of objects (notably for tests of resolution).

The purpose of this communication is: 1) to evaluate the BADT under the usual conditions in which it is employed, 2) to evaluate the BADT when only rather low frequency interrogating waves are used (in order to enable a substantial portion of the incident energy to attain the object and the detector after traversing a strongly-scattering host medium), 3) to examine the question of whether superresolution can be obtained with the BADT, notably for low-frequency interrogation and/or near-field measurements of the scattered field. These questions will be treated by employing both simulated and measured data pertaining to ultrasonic waves and fluid-like 2D objects. The conclusions of this study are also pertinent for electromagnetic wave BADT characterization of cylindrical dielectric objects.

Microwave Backscattering Tomography by a Projected Landweber Method

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The problem addressed in this presentation is tomographic reconstruction of dielectric objects from coherent backscattering measurements. As is known, the main difficulty in solving this problem is the nonlinearity of the operator that relates the measurement data and the unknown function (the dielectric contrast of the object under test). The development of accurate nonlinear data models has led to quantitative reconstruction algorithms, that can be applied virtually for whatever contrast values, but are normally very expensive computationally. On the other hand, the spatial resolution achievable from linearized data models and linear algorithms is strongly limited by the need to tune the wavelength to physically justify the linear approximation. Another possible approach is to use a linear data model and a nonlinear algorithm, which also exploits generic prior knowledge on the solution, such as compact support, reality, and positivity. The projected Landweber method [1] is one of these nonlinear algorithms, and solves a constrained least squares problem on the residual between measured and computed data. If compared with the fully nonlinear approach, this strategy promises significant computational advantages, and the quality of the solutions is much higher than the one obtainable from linear reconstruction algorithms.

The first-order Born approximation enables us to derive a portion of the Fourier transform of the object function from measurement data. The algorithm is capable to extrapolate the known spectrum, thus achieving superresolution. In particular, for backscattering-only measurements the Fourier data available are band-pass in nature, and the extrapolation must be performed towards both the high-frequency and the low-frequency regions of the Fourier space [2]. The projected Landweber method can be related to the well-known Gerchberg spectrum extrapolation algorithm and to the iterative POCS approach to reach the intersection of some closed and convex subsets of a Hilbert space [3]. The convergence of the algorithm is sufficiently fast for practical purposes, and can be further accelerated by means of a suitable preconditioning.

I will recall some of the theory and report the results of some simulated experiments on dielectric objects probed by means of a very simple monostatic illumination-measurement system. I will also mention the possibility of applying the same procedure to lossy dielectrics and to limited-angle data.

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Rytov Approximation and Optimization Based Algorithms for Solving Inverse Scattering with Experimental Data

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Diffraction tomography is an important alternative to straight ray tomography because it uses acoustic or electromagnetic radiation which is considered safe at low levels and it also involves measurements of object's refractive index which provide additional information.

Born and Rytov approximate formalisms for the field inside the scatterer are commonly used for imaging weak inhomogeneities. The Born approximation has been shown in practice to provide satisfactory results for scatterers of small size compared to the wavelength, under the condition of low contrast dielectric constant. In case of biomedical engineering applications, objects of very large size with low contrast are encountered, for both ultrasound (1-4 MHz) and microwave (400-2.500 MHz) radiation and when the tissue to be imaged is immersed inside the water.

We present an analysis of diffraction tomography of large size, low contrast dielectric objects. It is based on Rytov approximation and on the assumption that the unknown object is described by a superposition of Gaussian pulses placed on a rectangular grid array with unknown weighting coefficients. For both two-dimensional (2D) and three-dimensional (3D) cases and for plane wave illumination, an analytical expression for the scattering amplitude is derived which is a non-linear function of the unknown weighting coefficients. The squared error between measured data and predicted values for the scattering amplitude is minimized, by applying optimization methods. The inversion algorithm is tested on scattered field data obtained by analytical solution of the direct scattering problem for a known object of circular cross section (homogeneous or layered).

Furthermore, an experimental system has been set up for the evaluation of the developed algorithm. The object to be imaged is immersed in a water tank and is interrogated by an appropriate transmitter with a series of incident waves from various directions, while the scattering amplitude is measured at different positions. The receiver can be scanned along a straight line (2D case) or over a plane (3D case) by stepping motors which are controlled from a PC. The components of the complex wave field are detected, amplified, filtered and stored in the PC. The scattering amplitude is measured at every position of the receiver and at every view of the object and the collected data are used as inputs in the developed inversion algorithm; the unknown weighting coefficients of the Gaussian expansion of the scatterer that match in the best way the predicted values of the theoretical expression obtained for the scattering amplitude and the measured data are calculated.

The above presented method provides an efficient solution to the diffraction tomography problem associated with the imaging of soft tissues in biomedical engineering applications.

Imaging of Strongly Scattering Targets Using Cepstral Filtering

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The problem of imaging penetrable and multiply scattering targets from scattered field measurements has many applications. These range from medical and geophysical remote sensing to a variety of nondestructive testing tasks. The relationship between the far field scattering data, Y(r), and the scattering function, V(r), is an integral transform. More precisely, the Fourier transform of the scattered field data provides information about the product of V(r) with the total field within the target, convolved with a filter function, h(r). This filter function depends upon the number and distribution of measured data points available.

An approach to retrieving information about V(r) has been developed which makes use of cepstral or homomorphic filtering, a well known as a technique for removing multiplicative noise. The success of this technique, i.e. of this inverse scattering procedure, depends upon two factors, i) the degree to which the filter function h(r) deviates from a simple delta-function and ii) the choice of cepstral filter applied. In many of the real data and simulated data inversions performed to date [1] , the first concern has largely been neglected while the choice of cepstral filter has been limited to be a simple low pass filter.

Nevertheless, reconstructions have been quite good, albeit somewhat low pass filtered in appearance. In the work presented here we describe a pre-processing extrapolation step which diminishes the extent of h(r) making it more delta-function-like, and we examine the use of cepstral filtered tailored to the anticipated spatial frequency content of the field distribution inside the target. The benefits of these modifications, especially with regard to reconstructing images of V(r) with improved resolution and quantitative accuracy, will be discussed.

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Embedding Approach for Imaging Two-Dimensional Dielectric Objects

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In the past decade, many schemes have been proposed for determining the constitutive parameters of penetrable objects. Most of these schemes have been demonstrated first for the special case of a 2D dielectric cylinder illuminated by an electrically polarized two-dimensional wave. The environment typically consists of a single homogeneous medium or two homogeneous dielectric half-spaces. For such a configuration, the contrast-source integral equation for the field inside the cylinder becomes a combination of convolution and, for the half-space environment, correlation integrals. This makes it possible to evaluate the discretized versions of these integrals with the aid of FFT operations, which leads to relatively efficient computational schemes.

In practical measurements, the environment is usually not as ideal as described above. We mention in particular the set-up for determining properties of biological tissue that is being developed by the last two authors [1]. In this set-up, the object is placed in a metallic cylinder filled with water and multiplexed antennas are placed inside the cylinder around the object under investigation. Taking into account the presence of the metallic cylinder in the formulation of the contrast-source integral equation breaks the translation symmetry. As a consequence, FFT operations can no longer be employed. In geophysics and in antenna measurements, techniques like "deghosting", "multiple removal", "correction" or "calibration" are used to convert a complete set of scattering data for an object in the actual environment into equivalent data for a homogeneous environment [2]. To this end, sufficiently detailed field information must be available to allow a full spectral decomposition of the scattering operator on a contour surrounding the domain of interest. This prevents the application of such techniques in cases where a few configuration parameters must be determined from limited field information.

In that case, a possible alternative is to process synthetic data for an estimated object in a homogeneous environment instead of removing the effect of the actual environment from known data. To this end, the scattering operator for a synthetic configuration consisting of the estimated object in a homogeneous background must be combined with the response of the true background. This response then needs to be determined only once. This alternative has become feasible since combining the CGFFT method with a special extrapolation procedure as described in [3] has considerably reduced the computational costs of evaluating the scattering operator. This computation now requires an effort comparable to solving a few individual scattering problems with the aid of the CGFFT method.

In this lecture, the basic principle will be explained for the special geometry described above. Further, we hope to present numerical results that demonstrate the feasibility of the approach.

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Multifrequency Reconstruction : Analysis of the 1D Case

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In this talk we will investigate the improvement which can be obtained by using a multifrequency approach in an inverse scattering problem. Since we are not interested in the spatial dependency we restrict ourselves to the monodimensional case with a normal incident plane wave.

We will focus our study on the "one pixel" case. The reason being that we are now able to derive analytic formulae. First, we show for a monofrequency reconstruction, for some frequencies there is not a unique solution to the inverse problem. Furthermore, even in the case of uniqueness, there exists many local minima placed on both sides of the global one, and the levels of these minima can hardly be distinguished from the level of the global minimum. These results imply that the monofrequency approach is not robust with respect to noise disturbance. Nonetheless, when diminishing the frequency the local minima which are placed before the global minimum may vanish, but using a lower frequency diminishes the spatial resolution. Second, in the case of the multifrequency analysis, we show that as long as the number of frequencies increases, the global minimum appears more and more below the other minima which progressively disappear. So, even if the multifrequency reconstruction does not insure the convergence of any inversion algorithm, it nevertheless reduces the space of possible solutions and often helps the algorithm to converge to the right minimum. In all the cases, the multifrequency algorithm is more robust with respect to noise, so that one is always able to check wether the minimum which is reached is the global one or not.

Numerical Experiments on a Bilinear Frequency Hopping Approach to Inverse Scattering

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With reference to inverse scattering in an homogeneous background at a fixed frequency, the bilinear approach introduced in [1], considering as unknowns both the permittivity profile and internal field, allows to reliably and efficiently retrieve, as compared with the literature, a "wide" class of unknown profile functions. Performances of the approach can be furtherly ameliorated against possible "false solutions" problems by introducing alternative expansions of the unknown complex permittivity profile [2] which properly take into account the actual dimension of the space of data [3]. Even though the reconstruction capabilities of this approach are particularly fair, still some problems hold. As a matter of fact, the number of field unknowns rapidly grows with magnitude, bandwidth and extension (in terms of wavelength) of the unknown permittivity profile, causing the inversion procedure being trapped into "false solutions" which are indeed different from the actual one.

As a matter of fact, the operating frequency strongly influences the nonlinearity of the problem as well as the maximum achievable resolution. For example, when the frequency is low, on one hand, due to smoothing of the multiple scattering effect, the problem is more likely to be approximated with a "quasi-linear" model, but, on the other hand, since the information content of the data (which is related to extension of the scatterer in terms of wavelength), is reduced, the maximum achievable resolution will be poor. Therefore, a trade-off exists between the high and low frequency operation modes. Since the aim is to retrieve the highest possible number of parameters in a reliable way, the use of multi-frequency data can help to overcome this trade-off. The use of multi-frequency information, however, results in dealing with a large amount of data, causing a strong increase of the computational burden. In order to avoid such a problem by still taking advantage of the capabilities of [2], a bilinear "frequency hopping" approach can be envisaged, amounting to solve, starting from the low frequency regime, a succession of monochromatic problems. Whenever the low frequency spectrum of the unknown permittivity profile contains a not negligible part of the whole information to retrieve such an approach successively refines the estimation of the unknown object (achieving resolution capabilities related to the maximum frequency) by using the "low resolution" information as a reliable starting guess for the following steps. By virtue of the enhanced reconstruction capabilities of [2] with respect to linearized approximations, the proposed approach compares favorably with other "frequency hopping" approaches in retrieving the same dielectric objects by using a lower number of frequency steps (or starting from an higher frequency).

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New Results in Microwave Imaging Using a Genetic Algorithm

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In this paper we propose a novel approach for reconstructing unknown cylindrical dielectric objects (the cross section and the dielectric parameters are invariant along a direction) from the knowledge of the field scattered under transverse magnetic illumination (TM_z) conditions, in the case in which a set of different successive illuminations is used. The starting point for microwave-imaging approaches in the spatial domain is the Fredholm integral equation of the first kind, which relates the scattered electric field, $\mathbf{E}^{scat}(\mathbf{r})$ (measured in a suitable domain usually outside the test area), to the internal field, $\mathbf{E}^{tot}(\mathbf{r})$, and to the properties of the scatterer. Moreover, the inverse problem is recast into an optimization problem in which the solution is forced to fulfil also the *state equation*, i.e., the Volterra integral equation for the internal field. The problem is now to find a (global) minimum of a suitably defined functional $\mathcal{F}\{\tau(\mathbf{x}),\ \mathbf{E}^{tot}(\mathbf{r})\}$ (*fitness* function), which includes the information and constraints expressed by the above equations. Unlike in academic exercises, any practical application would require large discretizations, in order to obtain accurate resolutions for nontrivial scatterers; consequently, effective numerical algorithms should be applied and the use of as much *a priori* information as available seems, in our opinion, of fundamental importance. In the present work, we apply a genetic algorithm, which simulate the biological evolution of a *population* of tentative solutions by means of three operators: *selection* of the fittest element for reproduction, *crossover* and *mutation*.

The present approach was previously applied in the in the framework of the first order Born approximation [1]. There are several good reasons for considering the use of a GA. First of all, GAs have been found to be rather insensitive to *fitness* function details and to be robust in terms of capability to reach global minima [2]. Moreover, it is possible to insert a lot of a priori information into the solving procedure and they allow a natural implementation on parallel computers, that it seems to be the only possible way of dealing with a lot of data in a reasonable time. As an example, in Fig. 1 the reconstruction of a circular cylinder is shown.

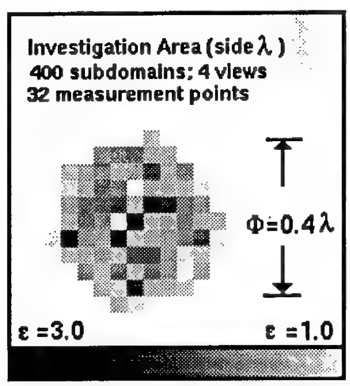

Fig. 1

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Inverse Scattering of a Multi-Layer Dielectric Cylinder Using Genetic Algorithm

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In this paper the techniques for determining the location, size, shape and/or dielectric profile of a 2-D object with layered structure are investigated using random neighborhood search and Genetic Algorithm (GA). Most traditional iterative inverse techniques use gradient type calculation of some continuous parameters and converge quickly if the initial guess is good enough. But, they tend to get trapped in local optimum solution unless a priori topological information on the object and some regulation methods are used.

The genetic algorithm is an optimization technique models the natural processes of evolution and selection via genetic recombination. The philosophy undergoing is survival of the more fit. Therefore, GA tends to yield global solution even when the parameter number becomes large, and thus, suitable for the inverse problem being investigated.

There are various ways to choose the parameters as the genes. Two kinds of genes are used in this study. First, we utilize a level-set approach, for which we assume the object is embedded in an environment of level 0, while the object may take up to L=2m-1 different levels. Then GA is used to determine the level profile of the whole object domain and the dielectric constant of each level. For the second approach, we expand the object domain into several cylinders with regular shapes (rectangular for example). Then GA is used to determine the size, location and dielectric constant of each cylinder.

In addition to GA, another hybrid technique combining the ideas of random neighborhood search and GA is used for the inversion of binary object. The method always starts with an initial population with uniform profile for the whole object domain and allows the boundary of each possible cylinder to evolve in two directions, i.e. extend and contract, in a random way. Then better species are selected into next generation as the GA does, and they will finally converge to the global optimum. Without any priori topological information, it is found that this hybrid method can yield the correct positions, sizes and shapes even with a uniform profile guess for the case of multiple cylinders. Various numerical results will be presented to demonstrate the capability of these techniques.

Session C05
Wednesday, July 15, PM 13:40-14:40
Room I
Parallel computation

Chairs : N. Simmons, M. Dubbard

High Performance Computation with 128 Nodes IBM SP2

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Introduction

In many industrial computations, an exact formulation of Maxwell equations is used to properly modelize the electromagnetic field. That is for instance the case when studying the low observability of a whole aircraft or when analyzing the radiation patterns of antennas after their integration on an aircraft. For this purpose Dassault Aviation designed in its electromagnetic simulation package called SPECTRE a dedicated computational tool based on integral equations. The associated matrix solver has been optimized through a partnership with IBM in order to take the best advantage of the computing power of the machine. In this paper we will present a computation that was performed on a duct which problem size was representative of an aircraft air intake at 5 gigahertz. This led to solve by gaussian elimination a complex linear system of about 360000 unknowns.

Simulation

The computation was made in order to study the scattering of the duct. Its geometrical and physical properties first allowed to change the system to two symmetrical systems of about 180000 unknowns each. The core of the computation was then to solve these two linear systems. This was made by use of an out of core method designed by Ali Mechentel, researcher at IBM T.J. Watson center. In this method you compute part of the gaussian elimination and store on disk the partial results in order to free the memory for further computation. This usually causes such methods to be much slower than in core solvers because the disk access is much slower than the memory access. But here the method was designed in such a way that computation on a block of data is taking place during the disk storing of the previous block and the disk reading of the next one.

Results

These concept lead to a very efficient method. The factorization of the two systems of 180000 unknowns each was here made in 115 hours and 20 minutes. This represent a computation speed of over 38,5 gigaflops which is about 63 per cent of the theoretical peak of the machine. And moreover this value is very close to the best speed obtained with in core method in the HPC Linpack benchmark on 128 nodes SP2 which is around 42,5 gigaflops on a system of 37000 unknowns.

Conclusion

This results demonstrate the efficiency of massively parallel computation using IBM SP2 for solving industrial electromagnetic problems. Thanks to such parallel computers numerical simulations that were previously inaccessible are now available for industrial use. Refined analysis involving exact formulations such as integral equations should therefore be more extensively used.

Domain Decomposition with Finite Elements for Microwave heating

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Finite Element analysis has been established as a powerful technique for the calculation of the electric field distribution inside microwave heating cavities. However, past research have shown that modelling even a domestic sized applicator can strain the computational capabilities and memory resources of modern workstations. In this paper, a domain decomposition approach is presented that can help to overcome this problem, and thus allow significantly larger structures to be modelled on existing computer systems. By subdividing the problem space into smaller, independent regions, not only are the total computer memory requirements markedly reduced, but also significant parallelism is introduced which can be exploited to reduce calculation time. An important feature, particular for microwave heating simulations, is that a region in the total problem space can be isolated from the rest. Its parameters (permittivity, mesh density, etc.) can then be varied, and new field patterns throughout the entire problem space recomputed very rapidly.

This allows different load-materials and configurations to be investigated. A parallel finite element domain decomposition program has been developed, using the Parallel Virtual Machine (PVM) public domain software for message passing. A direct solution approach was taken to overcome matrix ill-conditioning problems encountered in frequency domain FE analysis of heavily loaded closed cavities. Implementation issues of this program will be discussed, as well as experience gained using it on both a cluster of workstations, and a Hitachi SR2201 parallel supercomputer, available at Cambridge. Results of realistic microwave heating problems computed with this package will be presented and compared with experimental results. Conclusions will be drawn from the results about the usefulness of this technique.

Server-Client Strategies Applied to Computational Electromagnetics

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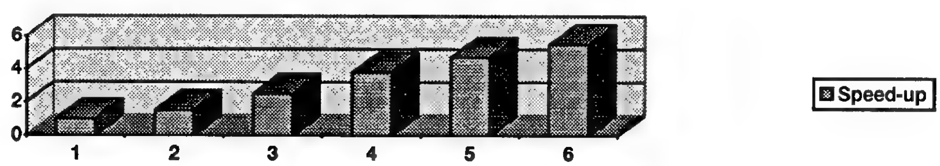
Introduction

Accurate circuit design involving arbitrary geometries and arbitrary material properties with the possible presence of linear and non-linear, lumped and distributed, active and passive elements, is a computationally demanding problem. A variety of mathematical methods exist to handle particular sub-sets from the range of possible situations. In order to solve very complicated problems we believe that it is necessary to adopt a heterogeneous approach, that is to couple independent methods together. Moreover, to keep the design cycle time reasonable, it is necessary to go beyond sequential computing. One cost effective, computational environment is distributed computing, that is, the use of available desktop and workstation computers, each likely to have different architectures, connected by a local area network [1]. The server-client paradigm is an ideal software model in this environment.

Distributed FDTD

Extending the work of Chew and Fusco [2], we have implemented FDTD server and client programs employing the scattered field FDTD formulation [3] where each client handles one geometric sub-domain of the problem.



The figure shows some measured speed-ups, in our laboratory, as a function of the number of workstations used for the test 3D problem given by Kunz and Leubbers [3]. In this test, an electric field having the form of a short Gaussian pulse, amplitude 1000 V/m, scatters from a sphere of lossy dielectric material surrounded by free space; the sphere has radius 0.48 m, dielectric constant four times that of free space and conductivity 0.005 S/m. The problem is solved on a grid of 34 X 34 X 34 Cartesian cells requiring 311 seconds (CPU time) in sequential mode. Further results will be presented at the conference.

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Session D05
Wednesday, July 15, PM 13:40-15:00
Room 120

Asymptotic M. Ney

Presentation of a Complete RCS Evaluation Chain : From CAD to RCS

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We present a new and complete RCS evaluation chain based on asymptotic high-frequency methods, including a CAD interface and a solver. This chain is able to deal with electrically large, general and complex targets, whose external skin is modelled by NURBS (Non Uniform Rational B-Splines) trimmed surfaces and is independant of the CAD system used to define the geometry of the object. This industrial chain is suitable for all targets which can present air inlet cavities.

The role of the CAD interface is very important in an industrial context. The interface functionalities are the following :

➤ Extracting the geometrical information necessary for the computation.Currently, IGES files are read (IGES entities 102, 110, 112, 114, 126, 128,142, 144). In a near future, SET files will also be read.

➤ Analyzing the wet surface aeras of the object, from a topological point of view. The classical B-Rep (Boundary Representation), which consists in the construction of the links between the faces, the edges and the vertices of the structure is generalized in order to take into account the most general trimmed surfaces (in particular, there is no restriction on the number of the bounding edges of a trimmed surface). For that purpose, a generalized DCEL structure has been developped. The internal wetted surfaces must be considered.

➤ Checking, characterizing and visualizing the object. In particular, the surface normals must be outwardly directed to allow a correct hidden face elimination and PO computation. RAM coating is introduced by means of surface labels. After processing, the interface writes a geometrical file (containing the geometrical information) and a topological file (containing the B-Rep structure).

In order to speed up the evaluation of geometrical quantities, each surface and curve, initially defined as NURBS, is internally converted by the Cox-De Boor algorithm into a set of rational Bezier functions (used as a low-level representation). However, the B-Rep deals with NURBS surfaces and curves, thus avoiding fictitious edges.

Assuming that the target is electricaly large, we use the main high-frequency methods to compute the backscattered field: Physical Optics (PO) and the Equivalent Currents (EC) for the scattering by the external surface and Shooting and Bouncing Rays (SBR) for the scattering by the air inlet cavities. A fictitious surface is used to close the cavities, in order to launch a beam of parallel rays. The computation of the scattered field requires the following steps : surface meshing and hidden parts elimination for PO and SBR, edge classification (free edge, G0 type edge, G1 type edge or material discontinuity) and discretization for EC. Note that PO is processed from the meshing of trimmed surfaces with automatic triangle subdivision in case of curved surfaces.

During the presentation, industrial applications dealing with complex objects will be shown, as well as comparisons with other methods.

CAD Based High-Frequency Monostatic RCS Prediction Code for Complex Objects : SERMAT

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The high-frequency monostatic RCS prediction code SERMAT, developed by Matra Bae Dynamics, is an hybridization of PTD and SBR methods. Calculated targets can be either metallic or totally or partially absorbing shapes, large with respect to the wavelength (missiles, tanks, ships, aircrafts ...).

Computation is performed on a CAD-like geometrical representation of the target, which is described in terms of facets using Matra Bae Dynamics' software library for geometrical simulations, INFOVISION (C). In SERMAT, this software is used to handle all the geometrical treatments necessary for the accurate evaluation of the RCS. As INFOVISION can read IGES files, SERMAT can be easily interfaced with all sorts of CAD files.

On a given target, the following interactions can be calculated :

- Simple reflections and diffractions : PTD is used. For diffractions in the absorbing case, diffraction coefficients that occur in the analytical expression of the currents are calculated using a 2D scattered field formulation.These currents also contain terms that take into account the incident direction of the wave and the orientation of fields.

- Multiple reflections : SBR is used, cavities can also be calculated. Specially in that case (cavities), the evaluation of the main curvature radii is of great importance. SERMAT can perform the calculation of those curvature radii without the help of any additional description of the cavity surface, only using the coordinates of the points of each facet and their normal vectors. Furthermore, for the case of double reflections, another method can also be used in SERMAT, based on a two steps PTD integration, numerically performed.

- Gaps, cracks and all sorts of geometrical defaults that can give rise to edge-diffraction- like electromagnetic effects can also be taken into account by the same type of 2D/3D transformation used in the absorbing diffraction case. SERMAT can be filled with 2D data of any origin (exact methods calculations, measurements ...) that are internally treated to give 3D results, in arbitrary case of incident direction and electromagnetic excitation.

The results in HH, VV, HV polarizations are simultaneously given at the end of a calculation, in amplitude and phase. When Ray Tracing is used, the output file can be treated to get statistical information on the number of reflections, the average reflection angles ...
SERMAT is written in Standard Fortran and can be run on various Unix workstations. Very little memory storage (10MO for the most powerful versions) is required. Special attention is given to ergonomic aspects as well as to CPU times.

CPU times (per incident angle on a IBM RS6000/380 workstation) typically vary between a few seconds or less for a complex shape with simple reflections and diffractions evaluation (depending on the number of facets) and 30 seconds for a 10λ length and diameter circular cavity calculated by Ray Tracing method with $\lambda/20$ ray discretization.

Some validations and CPU times examples are presented at the conference.

A Transfinite Moment Method Applied to Electromagnetic Scattering

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Introduction

Many electromagnetic applications involve the analysis of the scattering of an electromagnetic wave by a conducting or dielectric body. In this kind of problem the domain of interest is infinite and the numerical solution is often carried out using the Method of Moments (MoM) to solve volume or surface integral equations which automatically incorporate the Sommerfeld radiation condition. However these methods result in a full matrix representation and the large number of unknowns necessary to obtain accurate results represents a major numerical difficulty. To circumvent this problem, several authors have developed hybrid techniques (FEM-MoM, GTD-MoM,..). Another approach to reduce the computational needs is to improve the MoM itself for instance by enhancing the efficiency of the interpolation scheme. Following this idea, the use of the transfinite interpolation in the MoM is presented here.

This interpolation scheme can be applied to all the volume or surface formulations of the electromagnetic scattering problem and it is illustrated here in the case of an infinite dielectric cylinder illuminated by a TM wave. When dealing with penetrable cylinders, we are interested in determining both the scattered field and the induced field inside the dielectric. The well-known Richmond's formulation is used to obtain these results.

The transfinite method

The MoM generally involves the subdivision of the domain in small elements called patches or cells. In each cell, the unknowns are approximated in terms of simple interpolation functions. If we restrict the problem to the two-dimensional case, the approximation $\psi(x,y)$ of the unknown field $\phi(x,y)$ can be written in each cell :

$$\psi(x,y)=\mathbf{P}_x\mathbf{P}_y \quad \phi(x,y)$$

where $\mathbf{P}_x$ and $\mathbf{P}_y$ are the projectors on the subspaces spanned by the interpolation bases.

In the transfinite method, we consider another approximation $\pi(x,y)$ of $\phi(x,y)$:

$$\pi(x,y)=(\mathbf{P}_x+\mathbf{P}_y-\mathbf{P}_x\mathbf{P}_y)\,\phi(x,y)$$

This interpolation scheme is shown to be much more accurate than the classical one.

The results

After writing the MoM in an operator form to introduce the transfinite scheme, the so-called h- and p-versions of the transfinite method are applied to the scattering of an electromagnetic wave by an infinite dielectric cylinder. The transfinite and classical methods are compared in terms of the convergence rates of the RCS and of the electric field inside the dielectric. The results confirm the superiority of the transfinite schemes as predicted by the theory.

PO Analysis of the Scattering from Dielectric Flat Plates

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A Physical Optics (PO) analysis of electromagnetic scattering from dielectric flat plates is presented in this communication. The scattered field is obtained as the free-space radiation from two surface distributions of equivalent electric and magnetic currents, located at the upper and lower face of the plate. This implies the evaluation of surface integrals which however, by applying the Green's theorem, can be reduced to line integrals along the plate boundary S. Moreover, if S is a polygon, line integrations result in a summation of closed form expressions [W.B. Gordon, "Far-field approximations to the Kirchhoff-Helmholtz re-presentations of scattered fields," *IEEE Trans. on Antennas Propagat.*, vol. 23, pp. 590-592, July 1975].

Suitable PO formulas for the analysis of the scattering from anisotropic impedance flat plates have been recently proposed in [G. Pelosi, G. Manara and M. Fallai, "PO expressions for the fields scattered from anisotropic impedance flat plates," *Microwave Opt. Technol. Lett.*, vol. 14, no. 6, pp. 316-318, April 1997]. Here, it is shown that the field scattered by the dielectric plate can be expressed as the product of two terms: a shape factor and a material factor. The former depends only on the plate geometry, the latter on its electromagnetic properties. In the specific case of backscattering, the expression for the material factor simplifies and reduces to the reflection coefficient of the corresponding infinite dielectric slab, with the same electric characteristics of that composing the plate. Conversely, the shape factor coincides with the field scattered by the corresponding perfectly conducting plate. Consequently, the PO approximation for the dielectric plate Radar Cross Section (RCS) can be expressed as the product of the RCS of the corresponding perfectly conducting plate times the squared modulus of the reflection coefficient of the involved dielectric slab.

Samples of numerical results will be shown in order to check the accuracy of the PO approximation through comparisons with data obtained by a Combined Field Integral Equation (CFIE) formulation of the Moment Method. Finally, the case of dielectric windows opened in perfectly conducting plates will be addressed.

Session E07
Wednesday, July 15, PM 13:40-16:00
Room K
Global Modeling of Millimeter-Wave circuits : Part I

Organisers : Samir M. El-Ghazaly, Jim Harvey, Tatsuo Itoh
Chairs : Samir M. El-Ghazaly, Jim Harvey, Tatsuo Itoh

A Quasi-Two-Dimensional HEMT Model Coupled with a 3D FDTD Electromagnetic Simulation Software for Microwave CAD Applications

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Physical models are becoming increasingly important for active device characterization and design as their working frequency rises. However, because of the computational demands of most physical models, there is usually a compromise between simulation time and accuracy. Two-dimensional models are useful in device analysis, but are time consuming, and one-dimensional schemes can be inaccurate because of their simplicity. A good compromise exists in quasi-bidimensional models (Q2D) where the most important physical effects are included. The speed of the simulation is increased by a factor of 1000 relative to a two-dimensional scheme. This performance enables an interactive structure design. In this work we have coupled a Q2D model of a HEMT (high electron mobility transistor) with a 3D FDTD electromagnetic software. The typical modelled device is a III-V HEMT with a gate length of 1 to 2mm. This model may be applied to an AlGaAs/GaAs transistor, to pseudomorphic AlGaAs/InGaAs/GaAs or InGaAs/InP devices, but also to a IV-IV Si and SiGe transistor, if the material parameters are conveniently changed. The transition frequency for these transistors are actually greater than 100GHz. In the "hydrodynamic" approximation the HEMT model equations are :

Poisson equation
$$\Delta\phi = -\frac{q}{\varepsilon}\left(N_D - N_A + p - n\right)$$

Current conservation
$$\frac{\partial n}{\partial t} + \nabla.(nv) = 0.$$

Moment conservation
$$\frac{\partial\left(m^* nv\right)}{\partial t} + \nabla.\left(m^* nv^2\right) = qnE_x - \frac{m^* nv}{\tau_m}$$

Energy conservation
$$\frac{\partial(nw)}{\partial t} + \nabla.(nvw) = qnvE_x - \nabla.(nkTv) - \frac{n\left(w - w_o\right)}{\tau_w}$$

n is the carrier density, v the carrier velocity, m^* is the effective mass, w the electron energy, E_x the longitudinal electric field component, f the electrostatic potential. The relaxation times t_m and t_w are calculated for the channel material of the transistor with a Monte-Carlo material simulation program and given in a look-up table in the model. The three conservation equations must be solved for each carrier populations in the device i.e. electrons and holes. For a device with lower transition frequency (f_t<10GHz), the above model may be simplified to a drift-diffusion version where the current density is calculated using a carrier mobility which is doping, energy and field dependant. Passive lumped components (resistor, capacitor, inductor) must be included in the FDTD model to simulate external localized circuit elements as parasitic contact resistance and capacitance or bias circuit. Coupled to a 3D FDTD model, we have then the capability to simulate indoor communication systems at 60GHz or quasi-optical active antennas, but also lower frequency active devices.

New Trends in Modeling Electromagnetic-Wave Interactions with Semiconductor Devices and Circuits

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Semiconductor device simulation is a very powerful tool for understanding, development, and design of optimal devices. For a long time, device models were developed based on electric forces derived from Poisson's equation. Recently, the importance of using a complete representation of the electromagnetic fields inside high frequency semiconductor devices became more evident [1]. New models and simulation tools, that combines both electromagnetic waves and semiconductor device characteristics, tools are constantly being developed. The semiconductor device characteristics are taken into account using either equivalent circuits or physically-based models. These new trends are driven by the highly packed integrated microwave and mm-wave circuits, which create an immediate need for developing global analysis and design tools that combines all the circuit elements simultaneously. This approach requires electromagnetic interfacing of various elements such as semiconductor devices, passive components, radiation elements, and packages, which dictated the coupling of semiconductor device models with electromagnetic models. The semiconductor device model may very in complexity depending on the problem to be analyzed, the operating frequency range or circuit speed, and computational resources available.

This paper discusses the interactions between semiconductor devices and electromagnetic waves, and the possible ways to interface modern devices and circuits in the mm-wave range. This topic is very important for advancing current MMIC designs and for developing futuristic devices and applications. The recent developments based on various semiconductor device models, including equivalent circuit, hydrodynamic and Monte-Carlo approaches, will be reviewed. The models are coupled with a full-wave solution of Maxwell's equations based on the FDTD, and are used for studying circuits with operating frequencies from microwaves up to the optical range.

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Integrated Electromagnetic and Circuit Modeling of Large Microwave and Millimeter-Wave Structures

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An electromagnetic modeling procedure for electrically large microwave and millimeter-wave systems with circuit-field interactions is presented. The concept of an electromagnetic terminal is introduced to interface separate electromagnetic models of the blocks in a partitioned network.

Modeling large microwave and millimeter-wave structures using integrated electromagnetic, circuit, mechanical and thermal analyses is now within reach. Results from the convergence of available desktop computing resopurces and theoretical developments. One key ingredient is that the level of abstraction that microwave engineers are comfortable with has risen rather quickly over the last half decade. In this paper we present examples of the rise of abstractionism and in a speculative vein we present one scenario for achieving total system modeling. Electrical engineers are very familiar with the circuit level of abstraction and arguably the ability to work with physical systems at this level of abstraction is fundamental to electrical and computer engineering.

There have been a few attempts to model systems with interacting fields and circuit elements. In transient analysis of distributed microwave structures lumped circuit elements can be embedded in the mesh of a time discretized electromagnetic field solver such as a finite difference time domain (FDTD) field modeler. There are also commercial products that allow the interfacing of electromagnetic derived models with circuits but for now only fairly simple systems with a few ports can be handled.

The current work develops a network based model of the electromagnetic environment, whereby sections of the large electromagnetic structure are interfaced to each other at "electromagnetic terminals" and to the conventional nodal-based circuit at the ports. Each block is interfaced to a nonlinear network using normal current/voltage defined terminals. The exterior of the block is represented by multiport networks at the input and at the output. Each of the ports corresponds to one of the basis functions used in the discretization of the field at the slot. These input and output ports are denoted electromagnetic terminals to distinguish them from the current-voltage terminals of conventional circuit analysis. The electromagnetic terminals are defined in terms of incident and reflected waves. The interfacing quantities at the electromagnetic terminals can be of any type as long as the same basis is used for the evaluation of the networks on either side of the interface. In this work a method of moments (MoM) simulator was used and the interfacing quantities were the weighted basis functions of the incident and scattered magnetic field of individual cells. This is then a generalization of the scattering matrix concept with forward and backward traveling waves. The slot-microstrip-slot blocks were treated separately here as precautions (such as the use of photonic crystals) are taken in design to prevent direct cell-to-cell interaction. The aim of the overall analysis is to develop a single network representing the linear network with the minimum possible representation of the linear network. Generally a nodal admittance matrix with rank equal to the number of interfacing terminals is required.

Solenoid Inductors for Reduced Interaction with Silicon Substrates

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Integration of high-value and high-quality-factor inductors along with other passive components and transistors in an integrated circuit improves performance, reduces manufacturing costs. An application of particular interest is high frequency circuits, such as tuned amplifiers and filters, which require smaller inductance values as the operating frequency increases. Inductors of small value (in the range of less than 1 nH) are sufficient for tuned amplifiers in GaAs technology. They are also readily available due to the semi-insulating nature of GaAs material.

In silicon technology, lower frequency of device and circuit operation requires higher inductor values. This has Previously, inductors formed on both GaAs and Si substrates have been usually in the form of planar spirals. Spiral inductors by design force magnetic fields into the substrate. Due to the high loss of silicon substrates, inductor Q is usually low. There is also parasitic capacitance due to coupling to the silicon substrate which lowers the resonant frequency of the spiral inductor. Low Q and resonant frequencies forced designers to resort to the use of active inductors or inductor components external to the chip.

An objective of the present work is to provide an inductor which displays an increased self-inductance and improved quality factor (Q) not realized with conventional integrated spiral inductors. High valued inductors are obtained by forming a coil on the surface of the semiconductor with its center axis parallel to the substrate. This is in contrast to most prior work, in which planar spirals with center axes perpendicular to the substrate are employed. The solenoidal nature of the present structure allows the value of the inductor to be increased by increasing the vertical distance between the bottom and top conductors. This is possible without increasing the inductor die size, as is done in all planar spiral inductors.

This paper presents measurements of scale model solenoid inductors. The inductors are etched on dielectric substrates then a silicon substrate is added to form a multilayer structure. Two geometry have been built and tested. Solenoid inductors have shown less dependence on adjacent substrates including silicon. Losses and resonant frequencies in the presence of silicon are less for solenoids than spiral inductors.

Modeling Terahertz Radiation from a Photoconducting Structure Using the Kirchhoff Surface Integral Formulation

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The terahertz radiation arising from photoconducting structures, such as those used in electro-optic sampling applications and photoconducting antenna arrays, can be difficult to model. The difficulties are due in part to 1) the complexity in modeling the source of radiation which involves the interaction of electro-optically induced carriers with the electromagnetic fields generated in the structure [1], [2]; 2) the wideband nature of the radiation, up to and including THz frequencies, which generally precludes the use of frequency domain techniques; and 3)inhomogeneous material parameters which can introduce errors into analytical techniques.

The goal of the present work is to alleviate the modeling difficulties associated with inhomogeneous material parameters while accurately accounting for the wideband nature of the radiation in an efficient numerical method. We propose the use of a spatial and temporal transformation technique, the Kirchhoff Surface Integral Formulation, combined with FDTD [3]. In this technique, the near field radiation is calculated using FDTD, which allows incorporation of any number of material parameters. The computational domain is terminated with PML absorbing boundary conditions. The near field radiation on an imaginary surface around the device is transformed via the Kirchhoff Surface Integral to an observation point farther in the near field or in the far field. A detailed description of the Kirchhoff Surface Integral technique is presented, including the single infinite surface form and the closed surface form. The relationship between terms in the integral, which differs in the near field and the far field, is demonstrated via simple examples. Contributions from the various regions of the closed integration surface are shown to combine appropriately to provide a nearly perfect representation of the radiation at the observation point. Implementation is discussed and techniques for incorporation of the source terms are given. It is shown that the material parameters can play a significant role in the accurate determination of the far field radiation for the photoconducting structure. It is expected that this numerical technique may be applied to determine the radiation fields from a variety of ultrafast electronic devices.

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An Advanced Method for the Simulation of Nonlinear Circuits

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In the following, a method for the simulation of nonlinear networks is introduced with the help of the "Harmonic Balance" (HB) method. This method which is classified as a very efficient one referring to the numerical evaluation yields exclusively the solution for nonlinear problems in the steady state.

In order to limit the computing expenditure some facilitating assumptions have to be made. In integrated microwave circuits inductances are built in general with the help of metallizing structures which are always linear. There are only capacitive and ohmic nonlinearities to be considered. Furthermore, all controlled sources are driven by voltage. This fact is usually the presumption for most of the transistor models implemented for the simulation of networks in the microwave range.

The basis is a starting vector for the state voltage and the starting frequency obtained by a linear analysis. This starting vector contains the harmonics of all state voltages. With the help of the complex alternating current calculation the vector of the gate currents of the linear network can be determined from the state voltage. In order to compute the currents at the gates of the nonlinear network, the vector of the state voltages has to be inverse Fourier transformed. Then the searched currents can be calculated by using the relations valid for the nonlinear network in time-domain.

The complete calculation cycle is referring to the convergence a little bit more complicated. From the HB of non-autonomous systems it is known that convergence problems appear with high excitation amplitudes. These can be avoided by increasing the excitation amplitude stepwise. Thereby the results of the n-th step are used to compute the (n+1)-th step. In autonomous systems a synthetic source-value is introduced at which the real part of the first harmonics of the first state voltage is determined in order to achieve a stepwise increase. It should be mentioned that this method does not have to converge in all circuits. However, the algorithm is suitable to determine the state values very fast in analysed circuits (e.g. amplifier, oscillators).

The applicability of the method described above will be shown and discussed at examples of different circuits, e.g. at amplifier and oscillator circuits in microwave frequency range. These circuits were investigated and between the measured and simulated performances excellent agreement is observed.

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Session E08
Wednesday, July 15, PM 16:00-18:00
Room K
Global Modeling of Millimeter-Wave circuits : Part II

Organisers : Samir M. El-Ghazaly, Jim Harvey, Tatsuo Itoh
Chairs : Samir M. El-Ghazaly, Jim Harvey, Tatsuo Itoh

Novel Photonic Band-Gap Structures for Microwave and Millimeter-Wave Planar Circuits

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Photonic band-gap (PBG) materials are artificial, periodic structures which possess unique characteristics for the propagation and radiation of electromagnetic waves [1]. Recent advance in material processing and micromachining technology has made it feasible to synthesize three-dimensional PBG crystals which bare similarities in their behaviors to those of natural crystals of periodic atoms or molecules. Originated in the field of optics, such 3D PBG structures indicate the possibility of controlling the emission and propagation of single photons, which should have a deep impact on such fields as semiconductor lasers and optical communications [2].

The PBG concept is equally useful at microwave and millimeter-wave frequencies, with potential applications in high-Q cavities, advanced FSS, programmable filters, harmonic tuning elements and high-efficiency printed antennas. It is believed that PBG structures are able to provide an effective solution to several problems at millimeter wavelengths, including increased transmission line losses, lack of high-Q resonators, as well as increased surface losses for both planar circuits and antennas on dielectric substrates.

We have characterized a class of novel PBG materials which should find applications in microstrip-based circuits and antennas. Various types of 2D lattices including squares, triangles and honeycombs have been employed as synthesized substrates for microstrip lines. The lattices are realized either by drilling holes in the dielectric substrate or by etching periodic shapes in the ground plane. Both FDTD simulation and measurement have confirmed distinctive stopbands in these structures. Application of these PBG structures to harmonic tuning in microwave power amplifiers has been successfully demonstrated.

References

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The Use of EM Simulation in the Development of Avionics Products

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This presentation will examine the use and effectiveness of EM simulation for RF circuits and antennas in commercial and military Avionics. Specific characteristics of the avionics business ? such as significant regulation, strong focus on safety, long product development cycles (relative to commercial wireless) and long product lifetimes ? have a significant impact on the way that these tools are used. The relationship between these business characteristics and tool usage will be discussed. Case studies that describe where EM simulation has been used extensively will be presented and the effectiveness of that usage will also be examined. Both waveguide component and antenna design cases are considered. Finally, key EM simulation issues that need to be resolved to expand the common usage of these tools will be discussed.

Global Electromagnetic Characterization of CPW Nolinear Line

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Precise global simulation [1] of microwave circuits *and subsystems* has gained more and more importance with the progress of electromagnetic numerical *simulation techniques*. At millimeter frequencies and above, the electromagntic coupling *between distributed and lumped elements of a studied complex structure can't be handled tthrough the use of a classical circuit analysis software*. This can lead to errors in the circuit design and increase their developement cost.

The finite difference time domain (FDTD) method [2] has shown its capacity to analyse problems in a large frequency band by *performing only* one analysis in the time domain followed by a Fourrier transform. *It has* also shown its adaptability to take into account the effect of the insertion of lumped linear or nonlinear, passive or active elements into a distributed circuit *through the use of an extended FDTD formulation [3], or its proper cobination to the circuit simulator SPICE* [4]. In the second techni*que*, one can use all advantages of a SPICE transient analysis and all the *lumped* elements models of the software in a simple and powerful way. This is not the case *when using the first approach for characterizing structures containing complex lumped elements.*

In this paper we present an FDTD/SPICE global simulator for the circuit analysis. The conventional FDTD using Yee cell [2] is adapted to describe the circuit distributed part. The insertion of the lumped element is taken into consideration by establishing an equivalent circuit *for the circuit distributed part for each discretised cell and introducing inner ports at the cell or the group of cells to which the lumped element part is connected.* This inner port is defined by the voltage and the electric current crossing it, *which can be determined from the circulation of the electric field and magnetic field along paths supporting the lumped element respectively.* At each FDTD time step the electric current crossing the lumped element is computed by the FDTD method and given to the SPICE software *that analyses the electric equivalent circuit of the lumped element and computes the voltage at the lumped element at the next time step and this in turn is given back to the FDTDsoftware* . The SPICE transient analysis must be accomplished in a *time* equal to the FDTD time step...

This technique has been validated on *some test cases* [1]. Here we present an *interesting* application in the carachterization of a nonlinear line *operating il the millimetric range*. It's well known that the generation of electrical signals having a small descent time is essential for the correct performance of large band instrumentation devices. A nonlinear line formed by the insertion of a large number of Schottky diodes in parallel through the whole lenght of transmission line allows to achieve this goal. There is no rival for the coplanar waveguide (CPW) if *this nonlinear line* is wanted to be realised in MIC. This is due to the easiness of the connection of the lumped *nonlinear elements* parallel to the CPW and also due to the low dispersion characteristic of *CPW* line.

Transient response for a nonlinear CPW line containing 120 .Schottky diodes has been determined from this global electromagnetic simulation and compared to experimental results.

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Quasi-Static Analysis of 2-D Periodic Structures in VLSI interconnects

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Periodic structures have been widely used in microwave filters, frequency selective surfaces and antennas. The analysis technique of these structures has been well developed. However, the periodic structures also appear in the interconnects in VLSI, such as power lines, meshed ground and signal buses. Wu et al. proposed the analysis method for periodic interconnect structures occurring in VLSI[1]. However, the formulation proposed by Wu is confined to the 1-D periodic and homogeneous structures. In practical VLSI system the multilayered media is generally used and 2-D periodicity is encountered frequently.

In this paper, the 2-D periodic interconnect structure in lossy multilayered substrate is analyzed by the integral equation-moment method (IE-MoM). An efficient numerical method based on the complex image method and the Ewald sum technique has been used for the fast calculation of the periodic structures in multilayered IC substrates. In this method, the Green's function for a multi-layered medium is derived using complex image method[2], which converts the multilayered media Green's function into complex images in the homogeneous environment. Then, the whole problem reduces to the periodic problem in homogeneous media. The slowly convergent periodic Green's function is calculated efficiently using the Ewald sum transformation[3]. Therefore, the Green's function relevent to the periodic IC interconnect can be calculated rapidly, which results in the great savings in the computation time.

The proposed method has ben applied to the periodic crossover interconnect structures, and the results agreed well with measurements of the test pattern fabricated on IC's.

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Full-Wave Electromagnetic Deembedding of Monolithic Device of Arbitrary Layout Geometry

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Conventional method for deembedding the transistor's scattering parameters often requires on-wafer calibration standards to move in the two-port's reference planes to where the MMIC (Monolithic Microwave Integrated Circuit) layout starts. Followed by removing the contribution of the external, tapered portions of the layout using the electromagnetic analyses, the intrinsic two-port scattering parameters (usually common-source FET or common-emitter Bipolar) are obtained. Such method may fail to deembed transistor which is relatively small in the order of few microns or fairly versatile in geometry. In turn the device modeling mandates a new three-port deembedding technique. This paper presents the solutions for fulfilling the need and successfully deembedding the transistor with the reference planes right next to the intrinsic transistor's external interface positions, namely, gate, drain and source (See Figure A). Thus the deembedded scattering parameters are three-by-three indefinite scattering matrices [Sid]. The new technique extracts the indefinite scattering matrices using the measured two-port data with reference planes at probe's contacts (a-a' and b-b') and the multiport scattering matrices obtained by the rigorous full-wave electromagnetic modeling of the external arbitrary layout geometry. Thus the layout parasitics are completely removed, revealing the true scattering parameters for the intrinsic transistor.

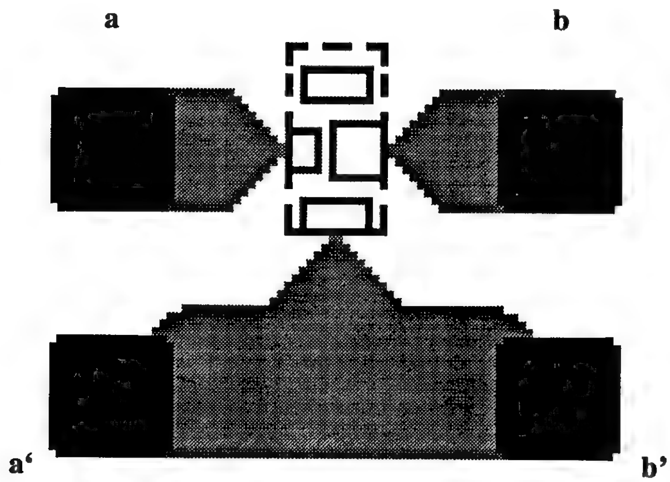

Figure A :
An intrinsic transistor (FET) embedded in external arbitrary layout geometry for contact probing.

RF Applications of Quantum Functional Devices (QFD)

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The QFD is a Heterostructure Interband Tunneling Field Effect Transistor (HITFET) which consists of an InAlAs/InGaAs interband tunneling diode integrated onto the source/drain region of a heterojunction FET with an InGaAs channel. The use of quantum functional devices (QFDs) in ultra-large scale digital integrated circuits requires the stringent condition of low static power dissipation be met. On the other hand, microwave circuits have a much lower integration level, and utilize devices that generally switch at high frequencies and are in the off-state typically only for a very short time. This relaxes the requirement on the peak-to-valley current ratio (PVCR) that can be obtained in QFDs that make use of the negative differential resistance (NDR) effect.

The NDR characteristics of the HITFET can be utilized to design VCOs and switched amplifiers. A VCO of this type was built and the measured RF characteristics of this Dual Voltage Controlled Oscillator (DVCO)will be discussed in this paper. A DVCO built by hybrid assembly achieved an oscillation frequency of 8.2566 GHz at an output power of 2.0 dB at Vds=2.0V and Ids= 8 mA. A phase noise of -129 dB/Hz was exhibited at 3 MHz away from the carrier. Corresponding phase noise at 2 MHz and 1 MHz away from the carrier were -124 dB/Hz, and -110 dB/Hz, respectively. In order to improve the output power and tuning range even further, a hybrid circuit was designed with two RTDs connected in series with the source of a HFET. The dual RTD VCO achieved almost double the power and tuning range than a single RTD VCO. The microwave characteristics of HITFETs were measured to generate equivalent circuit models to allow the design and simulation of a monolithic VCO circuit on an InP substrate. A Monolithic VCO was designed for portable communication application The simulated and measured characteristics will be reported. MMIC VCOs that incorporate HITFETs require fewer passive components when compared to conventional VCO. These type of circuits are very useful in future full duplex and half duplex communications circuits. The measured and modeled properties of Quantum MMICs will be presented at the conference.

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Session F05
Wednesday, July 15, PM 13:40-16:40
Room B/C
Active and Phased Array Antenna

Organisers : A. Roederer, G. Duret

Chairs : B. Arbesser- Rastburg, H. Steyskal

The Impact of Future Space-Borne SAR System Requirements on Active Phased Array Antenna Technology

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Presently, most of the European space-borne SAR activities are focusing on the development of SAR systems for achieving high geometric resolutions (<2 m) to be primarily compliant with military requirements and also with a number of civilian observation needs such as land topography and disaster monitoring. Moreover, the firm intention to install in the near future multi-frequency SAR systems on a single satellite, has set additional requirements for low system weight, large cost savings and reduced electrical prime power consumption. There is also a demonstrated need for variable swatch widths and resolutions, requiring a electronic beam scanning capability in azimuth and elevation. Future space-borne SAR systems will therefore use active phased array antenna technology, featuring high geometric resolution capabilities, low system weight and affordable acquisition costs.

In order to cope with high geometric resolutions, SAR systems have to operate with large instantaneous bandwidths. While the instantaneous bandwidths of present low resolution space-borne SAR instruments do not exceed 50-60 MHz, that of future high resolution SARs will approach 200 MHz and even higher, up to 500 MHz. Those large signal bandwidths will have a strong impact on the design of phased array SAR antennas in particular with respect to beam steering and array calibration. For a large signal bandwidth, beam scanning has to rely on time delay steering because phase steering introduces unacceptable beam dispersion and pulse distortion. Since switchable RF time delay devices are bulky and very lossy, a combination of phase and time delay steering is the preferred solution with phase steering at the T/R module level and a limited number of switchable time delay units at sub-array level.

For a small signal bandwidth, array calibration at a single frequency, usually the carrier frequency, is adequate to phase align all T/R modules over the whole signal bandwidth. However, for large signal bandwidths, the array calibration requires the compensation of the spread in the group delay of the T/R modules caused by fabrication tolerances, temperature drift and ageing effects.

In this paper the requirements of high geometrical resolution, low weight, reduced electrical power consumption and affordable acquisition costs on the design active phased antennas for future space-borne SAR applications will be discussed. Details will given on various approaches to meet these requirements. Especially the consequences on the array design of using time delay beam steering for beam scanning and those of array calibration in the time domain, will be highlighted.

A Novel Time-Domain Processor for Real Time SAR Operation

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Processing of Synthetic Aperture Radar (SAR) data, requires convolution of a sequence of echo data with a reference function that takes into account the acquisition geometry in building up the synthetic array. Real time processing for SAR data is very attractive for many civilian and military applications.

In frequency-domain, real, or quasi-real SAR processing is performed by using efficient FFT techniques and requires parallel computers and/or separable algorithms. Serious problems are encountered if the depth of focus is small compared to the pulse length and if range dependent motion compensation is needed. In time-domain SAR processing, above mentioned problems are not present, because depth of focus, range migration, motion compensation, parameter space-variance are immediately and easily taken into account by two-dimentional (2-D) time domain convolution. However, real-time implementation sets a significant constrain on the time allowed for each numerical multiplication: in this time a light wave travels a very short distance with respect to the azimuth resolution [1] !

For real-time implementation in time-domain with today's technology it is mandatory to use only the phase information of the SAR raw data. In this case multiplication operations are exchanged by sums; in addition, if we quantize the raw and reference phase on four levels, the operations can be performed by XNOR gates [2], [3]. This phase quantization can be simply obtained by hard-limiting the I and Q channels (one-bit coding) and it does not imply a significant loss in the quality of the final image: geometric resolution and interferometric phase both are preserved [4].

The proposed 2-D time-domain architecture splits the complex convolution in four real ones, each operating on binary sequences. Each 2-D real convolutor is assembled by means of parallel connection of 2-D real elementary convolutors. These operate with a limited number of columns of one-bit coded filter and raw data, and comprise a data formatter and a processing chip. The former reads serial data and addresses them to the processing chip in a column cluster. The latter is the main processing unit and provides the 2-D elementary one-bit convolution between filter and data.

The main processing unit implemented in a dedicated ASIC chip consists of a one to one XNOR operation between filter and data, followed by count of the resulting multiplications. In order to reduce area occupation, a tree adder structure has been implemented. Real time operations are implemented by clock frequency increase through a massive use of pipelining. After an initial delay related to the pipeline length, an image pixel is obtained every clock cycle. A full design and simulation results will be presented at the Conference.

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Performance of a small Digital Beamforming Antenna

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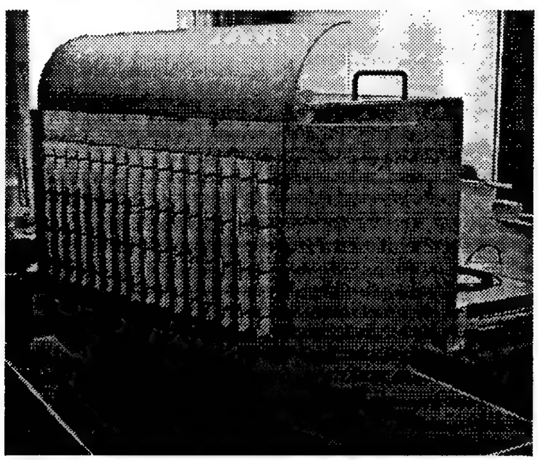
With digital beamforming (DBF), very accurate beam control can be obtained and various array signal processing methods can be applied. This includes multiple beams with very low sidelobes and adaptive pattern control, direction of arrival (DOA) estimation, space-time adaptive processing, etc.

This abstract considers design and performance of an experimental S-band DBF array aimed at radar applications. It has 12 digital channels arranged as a linear horizontal array, has an agile frequency band of 2.8 - 3.3 GHz and an intermediate frequency (IF) bandwidth of about 5 MHz. The AD-conversion is made at 25.8 MHz sampling rate with the IF at 3/4 of this frequency. The final filtering and down conversion is presently, together with the other digital, signal processing done digitally in the computer. The antenna and results are further discussed in the references.

The antenna array elements are stripline dipoles, arranged in a linear array of orthogonal linear subarrays with 4 dipoles each, giving vertical polarization. The analog receiver modules have high dynamic range and good out of band signal suppression. It includes a protection limiter, a step attenuator, amplifiers, filters and mixers, in which the received radar signal is transformed into the final IF at 19.35 MHz. The gain of the receiver modules are about 50 dB so that the noise RMS voltage is about 1.5 times the quantization step in the 12 bit AD converter. The IF bandwidth is 5 MHz and with 25.8 MHz sampling good anti-aliasing can be obtained using a simple filter.



Front view of the experimental antenna.

Since all individual antenna element signals are measured separately very efficient calibration methods can be used, correcting for gain and phase nonuniformity in the channels and their variations with signal frequency and for external, and internal, mutual coupling. This makes it possible to obtain very precise control of the conventional antenna patterns as well as adaptive sidelobe cancelling and good direction of arrival estimation performance.

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Current Modes for Microstrip Array Elements of Complex Shape

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To describe the current on a microstrip antenna element of complex shape typically requires on the order of 100 subdomain basis functions and thus the analysis of a finite array of (say) 100 elements leads to the order of 10,000 unknowns. This poses computational difficulties and makes a reduction of the number of unknowns desirable.

A microstrip patch element behaves physically like a cavity and the patch current can be closely approximated with only a few cavity modes. A rigorous analysis shows this to be true also for a rectangular patch in an infinite array environment and at all scan angles.
These characteristics motivated the derivation of the present set of `custom modes' for arbitrarily shaped patches. Our ultimate intent is to use these modes as basis functions for the analysis of finite arrays where they can potentially reduce the number of unknowns by one or two orders of magnitude.

In a recent paper [H. Steyskal, J. Herd, Electronics Letters, 32, No. 22, p.2036, 1996) we derived a set of physically motivated custom modes which provided good convergence but were mathematically unsatisfactory in that they were not linearly independent and not ordered with respect to significance. In this paper we derive an orthogonal, ordered set of modes with optimum convergence rate.

The custom modes are obtained from the patch current distributions in an infinite array. Using a method of moments analysis we determine the surface current j as a function of the spatial variables x,y and the scan variables u,v. Applying the Karhunen-Loeve expansion to the current j(x,y,u,v) we then obtain the desired modes which are functions of x,y only.

For the infinite array these modes will approximate the current with the least possible number of unknowns. Therefore, we may expect them to give a highly convergent representation also for the corresponding finite array.

We demonstrate the convergence properties over scan angle and frequency bandwidth by applying the modal expansion to several infinite and finite array configurations.

Transmit - Receive Antenna for ICO Satellite Operating in S Band (INMARSAT-P specification)

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The expansion of communication services with numerous mobile ground terminals of limited performances requires, for future satellite payloads, high performances in term of EIRP and G/T. The use of active antennas with multiple narrow beams of high gain provides the required flexibility thanks to their capacity to generate beams adapted in EIRP to the traffic deserved, to distribute the available RF power between beams, and to improve the service availability through a possible beam reconfiguration. A frequency reuse between beams accroding to a reuse pattern is also achievable.
The mission specifications considered are those of INMARSAT-P project with an ICO satellites constellation operating in S band. This choice of orbite imposes the use of large active antennas, with a high number of radiating elements, generating up to 100 beams.

A solution based on a single Rx/Tx antenna has been studied because, compared with separated antennas, it provides a better use of surface, an improve in mass budget, a mechanical and thermal simplification, and a better fiability compared to a deployable solution. However, it is more critical in term of intermodulation products (no space isolation between antennas).
The configuration finaly chosen is a direct radiating array (DRA) constituted of 151 identical radiating elements (RE). Its total diameter is of about 2 meters.
At receive, the 151 RE of the DRA are compliant with spatial isolation and G/T objectives.
A transmit, the best compromise is obtained with a rarified configuration composed of 127 active elements (151-24).
This solution is an original one and was patented because the 24 unused RE are all the same equiped of duplexeur and SSPA. Therefore, they constitute « cold redundancies ». In case of failure of some RE in transmit mode, a geometric reconfiguration consisting in switching on some of these redundancies, allows to get back complient EIRP and isolation performances, and therefore to keep a good link budget.

This concept of single Tx/Rx antenna is based on a triangular lattice. The RE has to be compatible with a 148.5 mm spacing in this lattice, and to provide a high directivity in a ± 25°, cone, for a 11% frequency bandwidth.
The design chosen for this RE is based on an Alcatel patent about « radiating element of variable directivity », because it provides a compact and light solution. The cross polarisation is reduced by optimising geometric parameters of resonators, but also with a controled difference of amplitude and phase at the 2 access of the inferior patch. All advanced technological model was designed in magnesium, and is compliant with all required specifications.
Finally, an intermodulation products (PIMP) study of this RE, based on INMARSAT-P specifications, has provided interesting performances. These results are encouraging, knowing that PIMP are the main drawback of this kind of solution.
Therefore, it would be necessary to realize a multicarriers testing bench more representative of system comportement, to improve this specification.

To conclude, this studie showed the faisability of a single Tx/Rx antenna and its equipments, compliant with an INMARSAT-P specifications

A Minimax Antenna Array Synthesis Applied to Optimization with Random Errors on the Excitation Coefficients

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We propose a minimax formulation and different criteria for antenna array synthesis problems. A simple way to resolve a minimax problem is to interpret it as an optimization problem under constraints. Then it can be solved using classical differentiable optimization tools. This method is used for optimization with random errors on the excitation coefficients. Finally, the obtained results are compared to classical method.

The criterion to minimize is the worst-case error with respect to a given pattern topography. The topography is described with two subsets of directions. The first one is the coverage area, power level is constrained by only a lower bound. The second one is called isolation area, power level is constrained by only an upper bound. The association of the chosen criterion and the unilateral constrained topography allows to improve the given topography.

To take into account random errors on excitation coefficients, the array performance is analysed with an approximation of the worst-case performance guaranteed for *p %* of cases. Then we apply the same formulation and the same method as previously described. The approximation is a function of the radiating pattern mean value and variance. We observe that for a given random errors density, the mean value and variance of the radiating pattern are analytical if EIRP pattern is calculated.

The advantages of this method are the improvement of the given pattern topography and the optimisation of the worst-case performance instead of the statistical analysis of the optimal solution.

A Beam-Switchable Active Microstrip Antenna Aray

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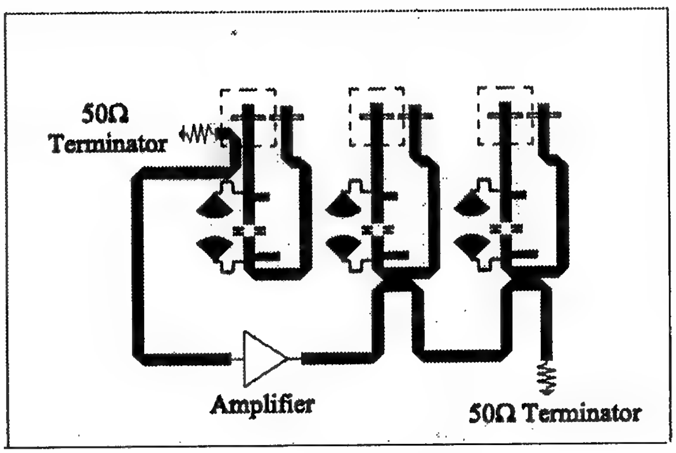
In this study an aperture-coupled microstrip active antenna aray with dual switchable beams was designed. The array was composed of several feedbackoscillators operating at 10GHz. Each oscillator contained a two-port aperture-coupled microstrip antenna located at the path of the oscillator loop (as shown in Fig. 1). Part of the oscillating power of the fist oscillator was drawn out to an external microstrip line and enlarged through an amplifier. The amplified signal was then injected to the rest oscillators so that frequencies and the phases of the oscillators could be locked.

There were two injection locking mechanisms ocured in the present design, which coresponded to two array radiation patterns. When the amplifier on the external line was switched off, the injection signal directly from the first oscillator disappeared, and the array oscillators were locked by the mutual injectionsthrough free space. The resultant radiation phase delay between adjacent antennas could be 0° or 180°, depending on the interelement distance. The other injection locking mechanism happened when the amplifier was turned on, under which themutual couplings through free space would be surpassed by the injection signal on the external microstrip line. The phase delay was then controlled by the electrical length of the microstrip line between adjacent oscillators. Several measured results will be presented at the symposium.



New Approach in a Problem of Account of Active Aerials

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Not die away constant interest to a problem of creation miniature of aerials (frequent range SW, USW and higher) with high sensitivity and/or wide passband. As a rule, this problem is decided by one of two ways :

1) creation short inductive of loaded aerials;
2) designing of aerials - amplifiers (AA) or active aerials.

To the decision of the second problem we are suitable in the given report.

Analysis shows, that depending on the purpose of integration and range of frequencies it is possible to allocate two ways of integration. In ranges LW, MW, SW and partially USW radiowaves the purpose of integration is, as a rule, reduction of the sizes of aerials and maintenance wide (a little octave) passband. In resonant AA the optimum coordination amplifieric of a device with a purely aerial for maintenance of the maximum relation a signal/noise in a receiving system is executed.

In a range centimetric (CMW), decimeter (DMW) and partially the meter waves (MW), for which develop usually resonant AA, as a rule, is not present necessity essentially to reduce the sizes of a purely aerial and purpose of integration improvement of sensitivity of receiving systems is.

Thus the algorithm of account resonant AA is represented following :

a) choice of a structure AA ;
b) account of a purely aerial, it electrodynamic of the characteristics and passband (being determining in a given system "aerial - amplifier") ;
c) account of a amplifier (account of stability, nominal factor of amplification, nominal differential factor of noise, nominal noise of number (if working frequency more than 100 MHz), source and target resistance) ;
d) account of a opportunity of the optimum coordination of a purely aerial and amplifier ;
e) updating of target parameters of a aerial and source parameters of a amplifier.

The main stages of account not resonance AA remain same, with only by correction, that the passband is calculated and for a amplifier, and noise of the characteristic of a amplifier are subject to account in any frequent interval.

The account electrodynamic of the characteristics of a purely aerial is conducted strict numerical - analytical methods.

The conventional account AA was conducted by a graph-analytical method, where to account of a purely aerial was not practically given attention (her static target characteristics) undertook only, and the account of a amplifier was executed on the basis of the theory of two-port networks. It resulted in rather approximate result. In a result the experimental operational development such AA was hardly whether a not main stage of work. The authors of the report offer on their sight the stricter decision, not breaking as a whole algorithm of the approach to a given problem. Along with with strict account electrodynamic of the characteristics of a purely aerial, the conventional two-port network of a active element of the circuit is replaced with adapted models:

- for a bipolar transistor - model Gummel-Pun (in simplified variant Ebers-Moll);
- for field of a transistor with managing p-n - transition - model Shihman-Hodzes;
- for field of a MOH-transistor of models LEVEL=4 (in simplified variant LEVEL=3, LEVEL=2, LEVEL=1).

Session G08
Wednesday, July 15, PM 13:40-15:20
Room M
Photonic Band Structures

Organisers : D. Maystre, G. Tayeb
Chairs : D. Maystre, G. Tayeb

15:20 ***Coffee Break***

Photonic Band Structure and Circuit Models for Perfectly Conducting Capacitive Grids

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We present an outline of the formulation for the characterisation of modes in a structure consisting of a square array of perfectly conducting cylinders. The modes are obtained by solving for the singular values of the Rayleigh identity, in the form discussed in a companion paper presented at this conference. We exhibit photonic band diagrams for both TE and TM modes, for wave propagation in the plane of the cylinders, and for wave propagation for the problem characterised by an incident plane wave making a fixed angle with the axes of the cylinders. We discuss the characterisation of the slope of the acoustic band (ie. the lowest band on the dispersion diagram), and exhibit analytic formulae for the slopes of the acoustic bands for both TE and TM polarisations in terms of equivalent dielectric constants for arrays of perfectly insulating and perfectly conducting cylinders respectively.

We also consider the problem of the scattering of a plane wave incident upon the array of cylinders at an arbitrary angle to the axes of the cylinders (each of which have length h). We solve the diffraction problem using a matrix formulation and, in the case of long wavelengths for which there is only a single propagating order, we construct analytic expressions for the reflection and transmission coefficients of the array for two particular cases. The first of these is for the case of h approaching zero, for which we derive an equivalent circuit model exhibiting capacitive behaviour. The second of these corresponds to h non-zero and the wavelength becoming large—in which case, the properties of the grid are equivalent to those of a uniaxial film characterised by two different refractive indices for each of the two polarisations. For either polarisation, the first of the refractive indices relates to the slope of the corresponding acoustic band and largely determines the phase change of a wave propagating through the film, while the second index derives from the static effective permittivity of the array and determines the Fresnel reflection and transmission coefficients at the air-film interfaces.

Parametric Analysis of Metallic Photonic Band-Gap Materials (MPBG)

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Metallic photonic band-gap (MPBG) materials are rising more and more interest in the microwave and millimeter-wave frequency ranges. At these frequencies, the metal can be considered as a perfect reflector and therefore confers to overall structure several behaviors which could be used in antenna and radome applications [1]. Several investigations have already been carried out using experimental approach [2] or parametric study [3]. However, none of them are able to give direct conclusions on the way of designing and realizing MPBG according to specifications.
In this study, we propose a theoretical and experimental parametric study. This leads to express simple laws relating geometrical parameters and electromagnetic behaviors.

The basic structure which has been studied is a square, rectangular or triangular lattice of parallel metallic wires, with a radius r. The periodicity in the two directions is defined by a and b. Therefore, the physical input parameters are defined as : the type of lattice, the lattice periods (a,b), the wire radius r, the relative permittivity of the material embedding the metallic parts, and the number of layers.
By changing these different parameters, we have determined empirical laws expressing the band-gap position, and the phase and slopes of the reflection coefficient versus the frequency and the incident angle of the plane wave. Propagation and free space modes coupling effects
have also been investigated in order to define and quantify the influence of the geometric parameters on them.

A first theoretical approach has consisted in developing a software based on the method of line. Even if the accuracy of such a method to characterize the real effects is not effective, changing the parameters enables to have a good estimate of the relative behaviors. Through this qualitative study, it has been shown several simple laws such as :
- increasing the period of the cell is reducing the first band-gap,
- multiplying the relative permittivity by a number n is equivalent as multiplying the period and the wire diameter by the square root of n.

More refined theoretical studies have been then carried out through HFSS [4]. This software shows good agreement when comparing with measurements obtained on prototypes.
Details of the simulation, the measurement and the laws which has been found will be given during the conference.

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Band Gap Properties of 2D and 3D Metallic Photonic Crystals

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In contrast with the dielectric photonic crystals, which in general present gaps limited to an octave or less, metallic photonic crystals present gaps extending from the null frequency to a cut-off value. Using computer codes based on rigorous scattering theories [1], [2], [3], we have investigated the properties of non-doped and doped 2D and 3D metallic photonic crystals made with thin perfectly conducting rods. The 2D crystals consist of parallel rods of infinite length, whereas the 3D cubic crystals studied here are made with rods parallel to the 3 axes of coordinates.

It will be shown that a 2D metallic photonic crystal can simulate a material having a plasmon frequency in the microwaves domain, as suggested by some authors [4], [5]. Indeed, the metallic photonic crystal behaves as an homogeneous material, and a very good estimate of the permittivity of this material at a given frequency can be given by a simple formula deduced from applied mathematics. For example, in the case of a square lattice of period d, denoting by r the radius of the rods, the homogenized permittivity is given by :

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega^2}, \text{ where } \omega_p = \frac{c}{d}\sqrt{\frac{2\pi}{\ln\left(\frac{d}{2r}\right)}}$$

This homogenization process can considerably simplify the problem of scattering by a metallic photonic crystal.

Comparisons between the 2D and 3D crystals will be given in order to investigate the analogies and differences in their behavior.

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Defect States in Metallic Photonic Band Gap Crystals

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Metallic Photonic crystals are becoming more attractive than their dielectric counterparts especially for applications in the microwave and millimeter wave regions. In those frequency regions metals are nearly perfect reflectors with low absorption while at optical frequencies they become lossy. Connected metallic wire meshes exhibit a full photonic band gap from zero frequency up to a finite cut off frequency which depends on the dimensions of the structure.

Metallic photonic crystals with cut off frequencies at the microwave [1], millimeter [2] and infrared [3] regions have already been constructed. On the other hand, isolated metallic patches have similar behavior with the dielectric photonic crystals. [4-6] An important advantage of metallic photonic crystals is that they could be smaller in size and lighter than the corresponding dielectric structures.

Using the transfer matrix method for the propagation of electromagnetic waves in dielectric and/or metallic structures, we present results for the transmission coefficient versus the frequency of the incident wave for different periodic structures. Results for the transmission at the top of the transmittance peak, the defect frequency and the quality factor, Q, are presented. For all the cases studied, the results compared well with experiments.

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Localized modes in two-dimensional triangular photonic crystal

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By using a finite-difference time-domain numerical method based on introducing an oscillating dipole at a proper position in a two-dimensional photonic crystal consisting of an array of dielectric cylinders, we numerically solve the inhomogeneous wave equation discretized in both space and time to calculate the eigenfrequency and the eigenfunction of a localized defect mode. We study the spatial distribution of the electric field and the radiated power associated with the defect modes produced by introducing a defect cylinder into an otherwise perfect two-dimensional triangular photonic crystal. We have obtained excellent agreement for the defect mode of A_1 symmetry created by removing a single cylinder from the center of the region of cylinders arrayed in a triangular lattice with the experimental result of Smith *et al.*(J. Opt. Soc. Am. B **10**, 314(1993)). We have also examined systems in which defect states are introduced by varying the radius of a single cylinder an when both the dielectric strength and the radius of the defect cylinder are changed. The calculated values of the donor and acceptor levels associated with the exponentially decaying defect modes of A_1 symmetry induced by changing the radius are in good quantitative agreement with the nondegenerate donor and acceptor levels reported recently by Feng *et al.*(Jpn. J. Appl. Phys. **36**, 120(1997)). By imposing boundary conditions appropriate to the irreducible representations of the point group C_{3v} we have also studied the defect states which belong to the A_1, B_1, B_2, E_1 and E_2 irreducible representations of the point group C_{3v}, and by varying the dielectric strength of an impurity cylinder we have determined under which conditions they occur within the photonic band gaps.

Session G09
Wednesday, July 15, PM 15:40-18:20
Room M
Superconducting Devices : from Gigahertz to Terahertz Technologies

Organisers : A. Kreisler, J. Sombrin

Chairs : A. Kreisler, J. Sombrin

Superconducting Technologies for the Future Millimeter and Submillimetre Wave Space Applications

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Observatoire de Paris, DEMIRM, URA CNRS 336 - ENS PARIS
61avenue de l'Observatoire - 75014 Paris - FRANCE

Introduction

The millimeter and submillimeter wavelength spectral bands, covering the frequency range 100 GHz (λ = 3 mm) to 3 THz (λ = 0.1 mm), represents one of the least explored yet information rich segments of the electromagnetic spectrum. This frequency span encompasses all of the critical spectral emissions from the key molecules involved in atmospheric chemistry on Earth (and on the planets and comets). These include those molecular transitions which have been identified as crucial to our understanding and monitoring of the global ozone depletion problem. The submillimeter-wave regime also contains spectral line emissions which can further our understanding of interstellar chemistry, new star formation and galactic structures. Due to high atmospheric opacity both astrochemical and stratospheric observations in the millimeter and the submillimeter -wave spectral bands must be made from high altitude aircraft : Kuiper Airborne Observatory (KAO/NASA) and SOFIA ; balloons : PIROG (SSC), Programme National d'Astronomie Submillimétrique (PRONAOS/CNES) or satellites : FIRST is designed to have broad spectral coverage beginning at 500 GHz and going up to 1.2 THz.

Super conducting tunnel junctions for heterodyne receivers

In the push to obtain ever higher sensitivity, shorter observation times and the use of smaller collecting surfaces, the submillimeter-wave astrophysics community has devoted much of their ressources towards the developpement of radiometer front-ends based on the superconductors niobium junction. At present, the most prevalent form of high frequency superconducting heterodyne receiver is the small area superconductor-insulator-superconductor Nb(SIS) tunnel junction which offers the potential of near quantum limited sensitivity throughout the millimeter-wave bands up to 700 GHz and possibly at frequencies as high as 1.2-1.4 THz with normal metal tuning stubs circuits (A1).1,2 THz could be achievable in the near future by using SIS with NbTiN superconducting junctions and 2-3 THz is achievable by using Hot Electron Bolometers heterodyne mixers. The SIS mixers must be physically cooled to temperatures well below the superconduction transition temperature, i.e. to 4 K for $Nb/Al_xO_y/Nb$ elements.

High Temperature Superconductor Planar Microwave Devices

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Since their discovery, the high temperature superconductor (HTS) thin film materials have been used to fabricate many electronic devices. On one hand, the superconductor materials exhibit low electromagnetic losses up to millimeter waves, so devices built with these materials are potentially very attractive. On the other hand, superconductor materials offer new possibilities due to their magnetic and temperature dependence.

In this paper, we will briefly describe a large number of these capabilities.

1°) Passive microwave circuitry

The basic of most passive microwave devices is the planar transmission line.

+ First of all, we describe a new technique to measure the characteristic impedance of short microstrip line.

+ Some results concerning low pass and band pass filters, phase shifters, couplers, multiplexers and lumped elements will be presented.

+ Interesting results have been achieved with an inverted resonator structure for which some particular results will be given.

2°) Tuning of the microwave circuit using a composite

Recently, an effort has been devoted to ferrite superconductor to built tunable devices like circulators, phase shifters or resonators. We will present a review of these possibilities and a possible modeling technique.

Non-Destructive Characterization of High Tc Superconducting Films and Applications

[1]Y. Roelens, [1]M. Achani, [1]N. Bourzgui, [1]P. Tabourer, [2]J.C. Carru

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Non-destructive characterization is the first step for applications with HTS thin films. The data obtained are mainly useful for the evaluation of the film quality and for modelling its electrical behaviour. We report two measurement methods : a one-coil inductance measurement, and a substitution method with a microwave cavity [1]. The characteristics of the three films studied are given table 1.

The first method is contactless and based on the measurmeent at 2MHz of a one coil inductance placed close to the film. The variation of the inductance Lm (see fig.1) as a function of temperature, is measured with a precision LCR Meter and gives a information about the quality of the film (for example, its critical temperature Tc=85K).

The second method uses a TE_{011} copper cavity at 36GHz. The measurement of the quality factor Q_0 for the whole copper cavity and the one with the HTS film allows to get the surface resistance Rs. In figure 2, we present the evolution of Q_0 as a function of temperature. The evolution of Rs is shown figure 3 and depends ont the films constitution.

In the communication, we will also present some realizations (microwave resonators) made from the films characterized in this work.

Superconducting material	Substrate	Origin	Ref
YBaCuO	MgO	L.C.S.I.M Rennes France	#1
YBaCuO	MgO	AAR Marcoussis France	#2
TlBaCaCuO	MgO	Superconductor Technologies USA	#3

Table1: Nomenclature of the HTS films

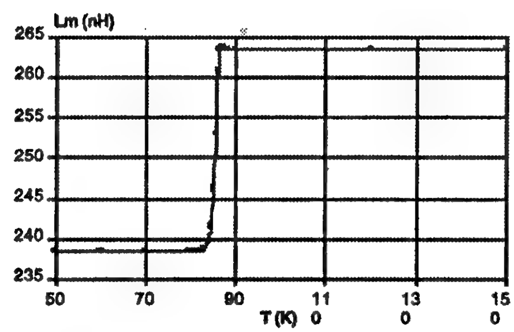

Fig1: Inductance of the self for the film #1 vs temperature at 2 MHz

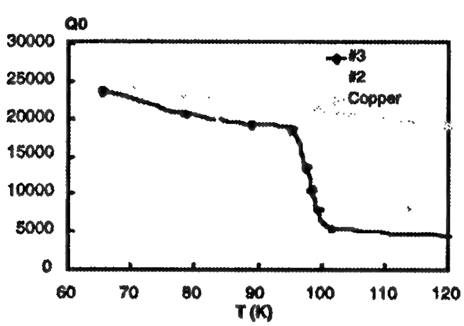

Fig2: Quality factor vs temperature

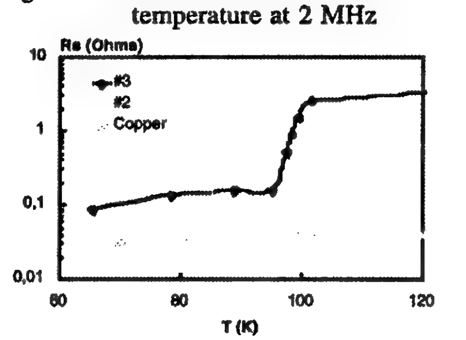

Fig3: Surface resistance vs temperature

[1] P. Lepercq, F. Mehri, N. Bourzgui, Y. Roelens, J. Dumas, J.C. Carru "Caractérisations Microondes et Magnétiques d'un film YBaCuO déposé sur MgO." 4ème journées d'Etudes, SEE, "Supraconducteurs à haute température critique", Caen (France), 27-28 mars 1997.

Planar SuperConducting HTc Antennas at 38 GHz

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The well-known high temperature superconductor $YBa_2Cu_3O_7$ is of first interest for microwave applications, leading to numerous studies about the growth of thin films on well-matched substrates allowing epitaxial growth as well as on low-losses substrates adapted to high frequencies specificities, like MgO or sapphire. It is of future importance to increase the working frequency at least to Ka band, essential for instance for wireless local area networks. This requires very high quality films and, in fact it has been shown that the pertinent parameter of the film, its surface resistance Rs, is strongly correlated to defects like large angle grain boundaries, necessiting an accurate control of the microstructure of the thin films.

For instance encouraging results have been obtained in the example of a single microstrip antenna operating at 38 GHz, and patterned from a $YBa_2Cu_3O_7$ thin film grown on a (100)MgO substrate : the HTS antenna efficiency at 80 K, relative to a silver identical patch working at room temperature, is 2.2 dB [1]. However, for the couple $YBa_2Cu_3O_7$/MgO, it is difficult to control actually the reproducibility of the surface resistance, due to the competition of two in-plane orientations of the superconducting material, leading to an array of large angle grain boundaries

So, new YBaCuO thin-films have been grown on sapphire substrates coated with a buffer layer of the cubic, well-matched and refractory cerium oxide CeO_2. Provided the thickness of the buffer layer and the growth temperature are well optimized, surface resisrances R_s in the range of 0.5 - 1 mΩ (77 K, 10 GHz) are reproducibly obtained. A comparison of the results obtained on the two type of substrates will be presented.

As the improvement of the superconducting antenna would be strongly related to the reduction of ohmic losses in the feeding lines, the use of a superconducting material in the distribution network of an antenna array composed of several patches is expected to be specially effective and will be discussed.

Reference

[1] X. Castel, Thesis, Université de Rennes, Octobre 1997

Terahertz Detection with Superconducting Bolometers

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Superconductors have offered this last decade a very large field of potential applications in the domain of electromagnetic radiation detection, due to the broad wavelength range and the various possible detection mechanisms offered by these materials. However, only two categories of detectors are actually operational for competitive performance in the submillimeter/THz range.

On the one hand, superconductor/insulator/supeconductor (SIS) tunnel junction devices used as heterodyne mixers offer very low noise level, but are frequency limited by the superconducting energy gap (about 1 THz for low temperature materials). Bolometric detectors on the other hand, although *a priori* less performant, have no intrinsic frequency limitation due to their purely thermal sensing principle. Moreover, their inherent slow response can be overcome by developing hot electron bolometer technologies, that allow promising output frequencies of several GHz with high-T_c superconductor (HTSC) nanostructures [1].

In order to implement wideband submillimeter wave detectors, ultimately of the hot electron bolometer type, various planar bolometric structures have been investigated. Indeed, one of the major problems arising in the submillimeter domain is to couple the incident radiation to the active detector region efficiently. As a matter of fact, conventional bolometric structures (such as single-body bolometers or composite bolometers with an absorbing layer) do not allow both sensitive and fast detector operation. In order to improve the radiation to device coupling, a wideband planar antenna has been used, whereas to improve the detector speed and sensitivity, a HTSC YBaCuO microbridge has been chosen. The working principle of such a detector is shown in figure 1.

In this preliminary study, two bolometric detectors have been built and tested, to cover the 30 µm to 1mm wavelength range. The first one consists of log-periodic antenna connected to a superconducting microbridge of a few µm^2 area [2].The second one uses a bow-tie antenna connected to a submicronic microbridge, associated with a coplanar waveguide structure for heterodyne mixer operation.

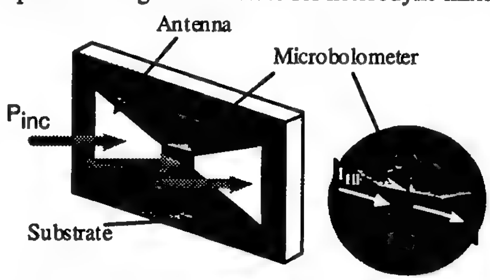

Figure 1 : Configuration of an antenna-coupled microbolometer.

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[1] B.S. Karasik, W.R. McGrath and M.C. Gaidis, J. Appl. Phys. **81**(3), 1581 (1997)

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Design of High Temperature Super Conducting Filters

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High temperature superconducting thin films are well suited to planar bandpass filters. The main disadvantage of these components, that is an important loss due to the normal conductor especially for very narrow-band can be eliminated by the use of HTS. The HTS device designers require a simulator capable of modeling complete structures with realistic geometries and physic characteristics, predicting the microwave behaviour and providing informations on the electromagnetic field and current density distribution.

Many commercially available CAD softwares permit the analysis of planar circuits (SONNET...) but they have some restrictions. In particular, they cannot take into account the anisotropic properties of some substrates like sapphire. In this case we use the three dimensional finite element method developed at IRCOM [2]. Whatever the software, the superconducting material is characterized by its surface impedance $Z_s=R_s+jX_s$. We use various models to describe the behaviour of R_s and X_s as a function of the temperature and the frequency like the model developed by professor VENDIK [1]. So we propose design and evaluate response of HTS planar filters. Elliptic response filters are attractive for multiplexers because of the improved rejection [3]. We present in this article, an original bandpass filter topology based on side-edged coupled L-shaped resonators which offers the possibility of having quasi-elliptic characteristics by simple means. Figure 1 shows the layout of a two-pole Chebychev filter. When the two excitation lines are extended in order to form a coupling air gap at its extremities, two transmission zeros can be observed on both sides of the bandwidth. The position of these zeros can be tuned by the value of the gap (figure 2). This idea can be applied to higher order filters.

The simplicity of the structure makes it practical to fabricate with HTS materials, after a first realization with gold metallization to validate theoretical results at room temperature.

References

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"High T_C Superconductor Microstrip Resonator on Sapphire Substrate (r-cut)" - *Proc. of 25th EuMC, 1995, Bologna, Nexus, pp.1205-1208*

[2] M. AUBOURG, S. VERDEYME, P. GUILLON
"Finite Element Software for Microwave Engineering" - *John Wiley, 1996*

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"Low Loss Multiplexers with Planar Dual Mode HTS Resonators" - *IEEE MTT, 1996, n°7, pp.1248-1257*

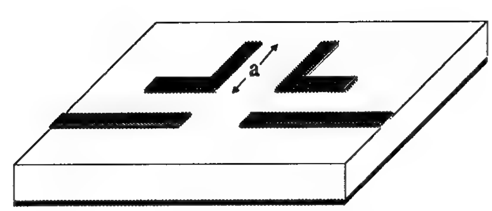

Figure 1 : Layout of a two pole Chebychev filter composed of two L-shaped resonators

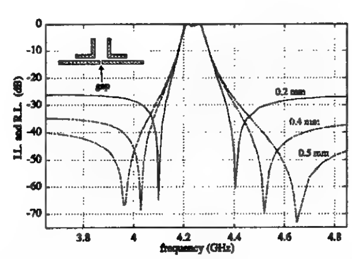

Figure 2 : Insertion loss response of the filter when excitation lines are extended for different values of the gap. The influence of the gap on the position of the transmission zeros can be noticed

Equivalent Models for HTC Superconducting Microscrip Discontinuities

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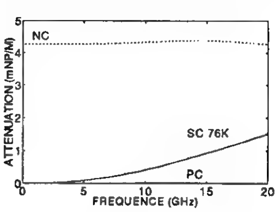
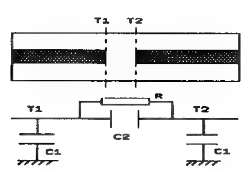
The purpose of this study is to determine an equivalent model of high-tc superconducting discontinuities. The FDTD method is used to discretize Maxwell's equations. The FDTD method is used to calculate the frequency-dependent characteristics of discontinuities. The microstrip discontinuities are the basic constituent elements of microstrip integrated circuits. Various microstrip resonators, couplers and filters can be analyzed from the inter-connection of microstrip discontinuities and microstripline segments. The study of superconducting microstrip discontinuities will allow to propose an equivalent electric model. With the two-fluid model, we assume that under the critical temperature, there are two densities of electron.[1]. The Gorter-Casimir model has been chosen to describe approximatily the proportion of electrons in relation with the superconductor utilisation temperature T. The FDTD method has been chosen for his efficiency and the facility to handle arbitrarily shaped structures such as microstrip discontinuities. This method solves, by using central finite differences, the Maxwell equations implemented in the cubic grid of YEE [2]. To obtain the superconductor conductivity in the time domain, we use a convolution integral where the electrical field is saved before the computation of new field.

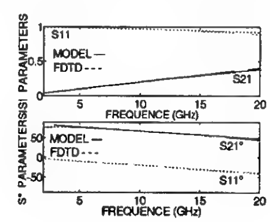
For the validity of results, we have simulated a microstrip gap dicontinuity [3]. The width of the metal strip is W=0.6 mm, the thickness of the substrate is H=0.6 mm. The choice of the dielectic is ε_r=9.6. The width of the gap is 0.3 mm. The superconductor is a $YBa_2Cu_2O_7$ microstripline with a critic temperature of 86.3 K and the utilisation temperature is T=76 K. The London penetration is 0.57 µm when T = 0 K. The superconductor conductivity is 3.9 10^5 Sm^{-1}. The conductivity of a non-perfect metal is 4 10^7 Sm^{-1}. We present the attenuation constant for a perfect conductor, for a non-perfect conductor and for a superconductor. Afterwards, an equivalent model will be presented.



1. Attenuation constant of a superconducteur (SC), a conducteur (NC), a perfect conductor (NC).



2. Equivalent electric model for a gap discontinuity.



3. Our results with: R=13.12 KΩ, C1=25.44 fF and C2=36.05 fF.

The FDTD method reveals itself an efficient tool to process superconductor discontinuities. These results will be used to introduce discontinuity models in the couplers, mixers and filters simulations.

This study is the topic of a *DRET* contract.

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Field Theory Investigation of The Nonlinearity of Microwave Superconductor Devices

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Recently, the advance of high-temprature superconductor(HTS) materials research bring us an exciting prospect of their applacations for microwave and millimeter-wave devices. Several authors have analyzed the characteristics of microwave superconductor devices. But they mainly used London theory to analyse the linear performanes of microwave superconductor devices. However, there are some nonlinear behavers of superconductors had shown in many experiments. In this paper, we used Ginzburg-Landau theory associatid with Maxwell equations for field analysis of microwave superconductor transmission line and their propagation characteristics.

The dimensionless GL equations can be expressed as follows:

$$\nabla\times\vec{H}=\frac{1}{2i}\left[\psi^*\left(\frac{1}{ik}\nabla-\vec{A}\right)\psi+\psi\left(-\frac{1}{ik}\nabla-\vec{A}\right)\psi^*\right] \qquad (1)$$

$$\left(\frac{1}{ik}\nabla-\vec{A}\right)^2\psi=(1-\psi)^2\psi \qquad (2)$$

where ψ denot the normalized order parameter, $\vec{A}$ is the vector potential of the electromagnetic field.

Now we will use the G-L equations to analyze microstrip line. Consider the structure of microstrip line with superconductor as shown in Fig-1. For the region 1,2,3 the TE and TM field components can be derived from the scalar potentials $\varphi_i^{(e)}$ and $\varphi_i^{(h)}$. $\varphi_i^{(e)}$ and $\varphi_i^{(h)}$ satisfy two-deminsional Helmholtz equations:

$$\nabla^2\varphi_i^{(e)}+\omega^2\mu\varepsilon_i\varphi_i^{(e)}=0 \qquad (3)$$

$$\nabla^2\varphi_i^{(h)}+\omega^2\mu\varepsilon_i\varphi_i^{(h)}=0 \qquad (4)$$

where i=1,2,3. For region 4, the G-L equations can be simplified to the following expression:

$$\nabla^2A^2=\left|\psi^2\right|A_z \qquad (5)$$

$$\frac{1}{k^2}\nabla^2\psi=|\psi|\left(|\psi|^2-1+\frac{A_z^2}{2}\right) \qquad (6)$$

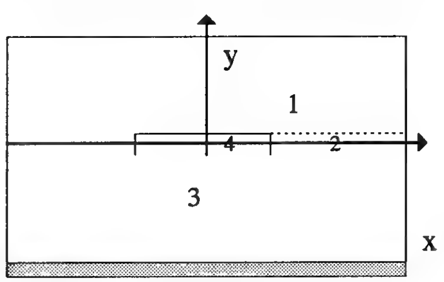

Fig-1

Since (5) (6) are nonlinear differential equations, to solve those equations, we use iterative method. First, let $|\psi^2|=1$, and solve equation(5) in region 4, solve equations (3) (4) in regions 1,2,3 and matched all the field conponent at each boundary. Then the zero order solution of A_z can be obtained. Next, we substitute the zero order solution into equation(6) and obtain the first order solution of ψ. Those equations combined with boundary conditions are solved iteratively until convergence.

Using this procedur mentioned above, the electromagnetic field distributions inside or outside the HTS can be obtained and the nonlinearty propagation characteristics are analyzed.

Session H05
Wednesday, July 15, PM 13:40-17:40
Room R02
Composite Materials II
Workshop on Complex Media and Measurement Techniques

Organisers : D. Jeulin, V. Vigneras
Chairs : D.S. Mclachlan, V. Vigneras

Investigation of the Electromagnetic Properties of Strongly Anisotropic Composites Made with Orientated Conducting Wires

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Heterogeneous materials are widely developed for optical and microwave applications because of their high performances. Indeed, for media made with particles embedded in a matrix, optical or high frequency properties can be controlled by the intrinsic properties of the particles and binder, but also by the structuration of the composite media. Among all these structures, we focus in this work on the electromagnetic properties of a special type of conductor-dielectric mixtures. By orientating conducting wires in a dielectric matrix, we propose original anisotropic composites which present a high contrast of permittivity between their eigenaxes : we call them C1D composites for composites Conducting along 1 Direction. We show that such strongly anisotropic materials can be used as reflecting polarizers or dichroïc components. In special cases, the Fresnel coefficients of an electromagnetic wave illuminating C1D composites exhibit the fact that it is necessary to determine the high frequency properties of such media only along some of their eigenaxes. So, in order to determine their permittivities and permeabilities in preferential directions, we have developed a broad band method which consists in adaptating the sample geometry to the fundamental mode in a coaxial line. Besides, we investigated the relationships between the electromagnetic properties of C1D composites and the characteristics of the inclusions. We particularly studied the magnetic losses which appear even in composite made of paramagnetic inclusions : we call it *artificial magnetism*. As the quasistatic approximation is not valid inside the conducting inclusions, we derive a model which takes into account the artificial lossy magnetic behaviour of these materials. We give experimental measurements that show very good agreements with this model. This special effect gives rise to a new broad band method for measuring the permeability of thin amorphous wires.

High Impedance Strongly Anisotropy Composites

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Magnetic composites consisting in a dispersion of magnetic particles in an insulating binder are commonly used for microwave applications. However, they exhibit rather low permeability levels, especially in comparison with bulk ferrites. Recently [1], we proposed a new class of composites materials based on ferromagnetic thin films with extremely large permeability levels and low permittivity when illuminated on the edge for one polarization.

These composites consist in an alternance of ferromagnetic and insulating sheets on the edge (sketched on figure 1a). They are called LIFE, for Laminated Insulator Ferromagnetic on the Edge. The microwave properties of LIFE composites will be presented on several examples. Figure 1b gives the microwave characteristics determined experimentely on a LIFE sample manufactured from a 2 μm thick soft magnetic coating on a 3.5 μm thick mylar substrate. The product $\mu_i.F_r$, of the measured initial permeability by the resonance frequency reaches 260 GHz, whereas it hardly exceeds 20 GHz in spinel ferrites, in accordance with the Snoek's law.

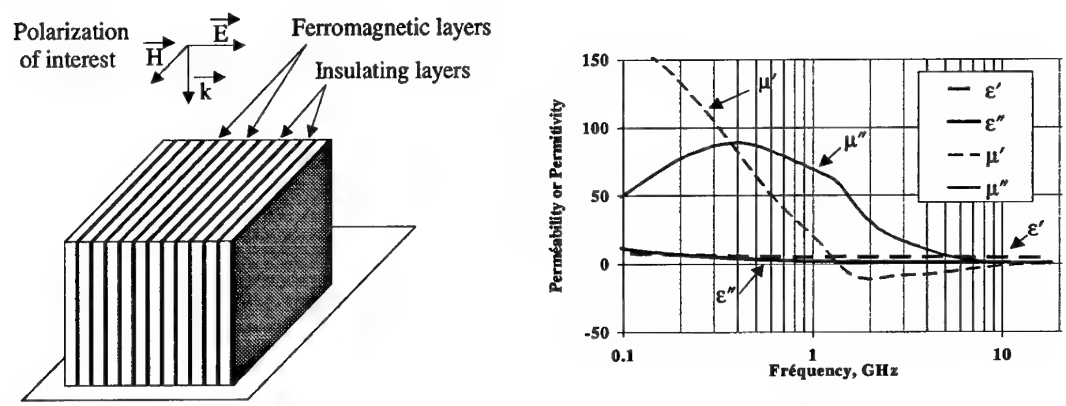

figure 1: a) sketch of a LIFE composite ;
b) typical radioelectric properties for the polarization of interest

Furthermore, LIFE materials can be depicted as anisotropic composites that are Conducting along Two Dimensions, C2D. In this more global description, we will introduce a new family of anisotropic composites where the arranged inclusions are magnetic wires parallel one to another, Conducting along One Dimension (C1D). Due to their strong anisotropy, it has been possible to derive simple expressions of the reflection and transmission coefficients on these composites [2].

As an evidence of the interest of such materials, we will discuss the possibility of engineering the frequency response. This can be done by adjusting the thickness of the layers, or also by colaminating sheets of different materials. Several achievements will be presented.

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Planar Composite Materials Made or Randomly Distributed Sticks : Modeling and Measurement of the Square Impedance in the Microwave Range

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The aim of the study is to determine what sample dimension allows us to characterize a heterogeneous material in the microwave range. For this purpose, we put emphasis on the role of characteristic homogenization sizes in the determination of effective medium properties.
We have performed a Monte Carlo numerical simulation of the reflection and transmission coefficients of a two-dimensional plane composed of randomly distributed conducting sticks, illuminated by a TEM incident wave. This method consists in determining the scattered field by integrating Maxwell's equations on a periodic realization of the plane. This is done by randomly dropping sticks per unit surface on a square of side T, periodically repeated in the homogenization of this medium and tends to a steady value bryond a characteristic length Tc. At this stage, we have to define an intrinsic parameter for a two-dimensional material : the square impedance. Measurements in the frequency range 2-18 Ghz have been crried out in free space in a broadband lens focusing facility. Numerical results, effective medium theory results, and measurements are in fairly good agreement.

Measurements of Universal and Non-Universal Percolation Exponents in Macroscopically Similar Systems

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The conductivity (σ_m)and dielectric (ε_m) of percolation systems obey the equations : $\sigma_m = \sigma_c (\phi - \phi_c)^t$ for ($\phi > \phi_c$); $\sigma_m = \sigma_i (\phi_c - \phi)^{-S}$ and $\varepsilon_m = \varepsilon_i (\phi_c - \phi)^{-S'}$ for ($\phi < \phi_c$); where ϕ_c is the critical volume fraction of the conductor ($\sigma = \sigma_c$) and σ_i is the conductivity of the insulator. Computer simulations, measurements on model systems and many continuum percolation systems, when fitted to these equations, give the universal or close to universal values of s and t (0.87 and 2.0 respectively). However, some continuum systems give rise to t values larger than the universal value. The present work tries to find out why many conducting systems have abnormally high t values and why the AC (dielectric) and DC (conductivity) s values do not agree.

Experimental results will be reported on systems consisting of different conducting powders (scale 3 - 10 μm), whose macroscopic distribution (scale 300 μm) is determined by the size of the insulating grains, upon the surfaces of which, the various conducting powders distribute themselves differently. The different links, blobs and nodes resulting from this lead to a wide range of intergrain conductance distributions and hence, we believe, different values of s and t. DC conductivity results will be presented for systems in which the conducting powders; ground Carbon Black, ground Graphite, ground Graphite/ Boron Nitride (with the Graphite + BN ϕ fixed at 0.15), Nickel powder (magnetic) and Niobium Carbide (superconductor) were each mixed with Talc-wax as a common insulating matrix. The usual DC percolation parameters (ϕ_c, t & s) were obtained from fitting the results to the percolation equations. Almost identical results were obtained by fitting to the modified GEM equation. The low ϕ_c values obtained (0.01-0.07) are generally in agreement with the Kusy model for small conductor particles embeded on large insulator particles. Values of t very close to the universal were obtained for ground Carbon Black and Graphite (2.06 & 1.93 respectively). A low t value of 1.5 was found for the Nickel system while an exceptionally high t of 5.3 was measured in the Niobium Carbide system. In the three component system (Graphite/BN/Talc-wax), t was found to be 2.5.

In addition, 1/f or flicker noise results on the conducting side ($\phi > \phi_c$) on the these systems, which gives the exponent ω from the relationship $S_{AV}/V_{dc}^2 = KR^{\omega}$, will also be presented. Measurements done on ground Carbon Black, Graphite/BN and Niobium Carbide systems show the exponent ω taking a different value ω_1 close to and ω_2 further away from the percolation threshold. The values of ω obtained (1.0 - 3.0) appear to be consistent with the different types of contacts; from the noisy and Sharvin metallic type to those in the Maxwell conduction regime. Suggestions will be put forward to explain the observed trends in the results.

Optical Behaviour of R.F. Pulverised Au-Al_2O_3 Thin Cermet Films at Oblique Incidence under Polarized Light. Thickness Effect when Crossing the Percolation Threshold

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We study the optical behaviour of thin cermet films with various composition and thicknesses, below, above and crossing the percolation threshold. Measurements of the Reflectance R and the Transmittance T under both S and P polarizations (perpendicular to or in the plan of incidence) have been performed in visible and near infrared regions, under several incidences included normal one. Because the electrical field of the wave has a component perpendicular to the film in P polarized light, one expects a geometrical anisotropy effect on the dielectric function : the interaction between light and the film may be different when propagation has the direction of the thickness, which means along a short limited direction and in the perpendicular one, which corresponds to macroscopic scale. As a matter of fact the thickness is smaller than, or of order of, a relevant length, which has to be compared with the percolation correlation length. Taking into account the dependence of the percolation threshold on both the thickness and the concentration in metal, we have performed measurements on a lot of samples, in correlation with the electrical D.C. conductivity, with various filling factors and more or less in the vicinity of the percolation threshold. With normal incidence measurements, it is possible to determine the dielectric function, to calculate the expected reflectance and transmittance of the corresponding homogeneous medium and then to compare with experimental results to point out possible discrepancies.

Non-Linear Electrical Behaviour of Carbon - Polymer Random Composites

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We will report an experimental study of the electrical behaviour of composites made of a thermoset (epoxy resin) filled with conducting carbon microbeads (about 10 μm diameter) as a function of filler content, heat exchange with the environment and other electrical parameters. It had been demonstrated a few years ago that these composites exhibit, when they are uniformly heated above room temperature, a large positive coefficient of temperature (PTC) for the resistance. We show that, due to Joule heating and thermal contact with a thermal bath, two types of non linearities are exhibited constant intensity. We have also studied the responses of the materials when they are subject to steps of either variable voltage or variable intensity. Typical response times are of the order of minutes when moderate overvoltage or overcurrent are used and when the coupling to the thermal bath is efficient. Most of the experimental behaviours are in good agreement with a model of random fuse network, as well as a scaling approach based on percolation theory with random bond break under heating. Finally, as the mechanism of the PTC effect is essentially due to the loss of interparticle contact induced by the matrix thermal expansion, we show that it induces an extra noise, which adds to the usual 1 / f noise. We have analyzed the power spectra and the time dependence of this noise with various values of the biased current: we found that, as expected, this noise is large at low and very low frequency and that it is multifractal.

Enhancement of Nonlinear Response in Metal-Dielectric Composites near a Sharp Quasi-Static Resonance

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The quasi-qtatic resonances of a metal dielectric composite occur at special values ef the electric permittivity ratio ϵ_I/ϵ_M , when the bulk effective electric permittivity ϵ_e diverges. This can occur only when that ratio is purely real and negative. Therefore those resonances can only be aproached if the frequency ω of the a. c. electromagnetic (EM) fields is in the region where ϵ_M (the permittivity of the metallic component) is almost real and negative, while ϵ_I (the permittivity of the dielectric component) is almost real and positive.This means $T^{-1} \ll \omega < \omega_P$, where T is the conductivity relaxation time of the metal and ω_P is its plasma frequency, i.e., the wavelength λ must lie in the infra red optical range. In order for the quasi-qtatistic approximation to be valid, the size ℓ of the metallic inclusions must be smaller than the EM skin depth, i.e., for $\lambda = 10$ µm, we must have $\ell < 100$mm. The quasi-static resonances will be sharp and well separated from each other either if the inclusion density is low, or if the inclusions are all identical and arranged in a periodic array. When all of those requirements are satified, it is possible to achieve a grest ehancement of the macroscopic nonlinear EM response of the composite.

In order to be specific, we consider the case where the permittivity of the dielectric component depends on the magnitude of the (local) electric field $\mathbf{E(r)}$ in the following fashion :

$$\epsilon_I = \epsilon_0 + b|\mathbf{E}|^2.$$

The ehancement of ϵ_e is then the result of two effects : (a) Near a resonance the local electric field $\mathbf{E(r)}$, which is usually position dependant in a complicated fashion even for simple microstructures, is much stronger than the volume averaged or externally applied field $\mathbf{E}_0$. (b) Near a resonance the field dependant part of ϵ_I , mamely $b|\mathbf{E}|^2$,is competing not against the field independent part ϵ_0 , but against a "detuning parameter", which measures how far away the system is from against nonlinear behavior can be observed near a resonance even though $b|\mathbf{E(r)}|^2 \ll \epsilon_0$ *everywhere in the system* ! These ehanced forms of behavior include potentially useful phenomena such as intrinsic optical bistability and generation of a.c. fields at higer harmonic frequencies (the letter requires a different type of nonlinearity than the one assumed above).

The fact that these phenomena can be observed even while the local nonlinear behavior is weak everywhere is very convenient from a theoretical viewpoint.It enables us to develop very efficient approximation schemes which are based upon treating the local nonlinear effect as a small perturbation to the leading liear behavior. In particular, we have used a "zero virtual work" principle in order to discuss intrinsic optical bistability in such systems, and an expansion in powers of the nonlinearity coefficient (b in the above equation) in order to discuss harmonic generation.

Analysis of the Frequency Behavior of Composites Polymer/Conducting Polymer

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The study of the electrical properties of conducting composites made on a large frequency band shows a set of characteristic features. The composites are heterogeneous materials made up of two polymeric phases, one insulating phase (Polymethylmetacrylate PMMA), and one conducting (polypyrrole PPY).

i- In the low frequency range, the conductivity is described by the percolation theory, however the percolation threshold p_c depends on the frequency if the analysis is made from the conductivity behavior versus PPY concentration :

at $\omega = 0$, $p_c = 5\%$ whereas at 43 MHz $p_c = 12\%$

at $p > p_c \quad \sigma_m = \sigma_0 (p - p_c)^t \quad t = 2$

ii- The behavior of the conductivity versus frequency is well represented by :

$$\sigma(\omega) = \sigma_m \left(1 + \left(\frac{\omega}{\omega_0}\right)^s \right)$$

where σ_m is the dc conductivity and depends on the PPY concentration. The variations of s measured as a function of PPY concentration show a rapid fall at the percolation threshold p_c which can be explain by an asymptotical behavior in the IR range, the same for every concentrations.

iii- Permittivity behavior :

$\varepsilon(\omega) \propto \omega^{-u}$ with $s + u \approx 1$ in the range 100 MHz-3 GHz.

Optical Absorption in Simulated Fractal metal films

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Optical and electrical properties of nanocermets and granular metal films present a special behavior near and at the percolation threshold, where they exhibit fractal structures : mainly, a large infrared absorption in the phase transition region governed by the percolation power laws. Moreover, this absorption is frequency independent in the whole infrared range.

In a first time, the real space renormalization method is used to investigate the site percolation transition into Random-Sierpinsky-Carpets with various scale invariance ratio n ($n \in N$). It is shown that the fixed point of the renormalization group (i.e. the percolation threshold) is not unique but depends on the number k of segmentation steps used to generate the fractal. The sequence of fixed points is increasing with the number of segmentation steps and converges, when $k \to \infty$, toward a limit strictly less than 1 which can be considered as the percolation threshold for these structures.

In a second time, the same approach is used to determine the effective dielectric function and the optical absorption of these simulated films. In each Kadanoff's block, a local effective dielectric function is calculated using a classical effective medium theory and the procedure is repeated at each renormalization step. This approach has been seen to correctly predict the metal-non metal optical transition. Nearby the classical absorption maximum, secondary peaks appear which are attributed to the various percolation thresholds by fitting the effective dielectric function with a model including the classical exponents of percolation.

The absorption peak of actual granular metal films near the percolation (fractal with $n \in R$) is never correctly predicted by effective medium theories. It is expected that this absorption peak is the envelope of secondary peaks associated to the various percolation thresholds predicted here with an integer scale invariance ratio.

OPTICAL BEHAVIOUR OF R.F. SPUTTERED Au-TiO_2 THIN CERMET FILMS : INFLUENCE OF THE PARTICLES SIZE AND THE GOLD CONCENTRATION.

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We study the optical behaviour of Au-TiO_2 cermet films, obtained by R.F. co-sputtering of small gold pellets disposed on the top of TiO_2 target in a reactive gas ($Ar + O_2$). The gold volume fraction is varied in the range 10^{-3} to $5\ 10^{-2}$. The thicknesses are all of order of 400 to 500 nm. In this low concentration range the optical behaviour is mainly governed by the gold particles size which very much depends on the deposition substrate temperature (up to 400 °C) and the annealing time (up to 24 hours) and temperature. The mean diameter (~ 20 nm) of the metallic particles is obtained by X-ray diffraction and / or by transmission electron microscopy (TEM). Measurements of the Reflectance R and the Transmittance T at quasi-normal incidence have been performed in visible and near infrared regions (300 - 2500 nm). Using a short pulse Nd-YAG laser, we look for third-order nonlinear optical behaviour due to the enhancement of the electromagnetic field close to the surface plasmon resonance of the metallic grains.

Optimization of Radar Absorbing Honeycomb by inverse method and morphological observations

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The radar absorbing honeycomb is an excellent material for the applications as the stealthy structures. Associated to transparent and absorbing skins, it allows for hard-wearing and light mechanical structures. AEROSPATIALE has developed an industrial producing bench, with the capacity to manufacture blocks of 1*1*0.3 m (possible to extention to 2*1*0.6m). The means of manufacture allow to realise boards from a few millimeters of thickness up to several centimeters, in a range of permitivity in the ratio of one to five for example.

To answer the needs of a RCS model, we use an inverse 2 D or 3 D numerical method to choose the best configuration for the material properties, thickness and permitivity.

A micro structural observation of the honeycomb and its absorbant resin makes sure of its correct microwave properties. The use of a numerical code where the honeycomb cells are modelized using impedance and conduction characteristics allows to optimise the process of the finished product. With this method, we can produce cheap material and warrant good performances in the microwave region (from a few MHz to 30 GHz)

J. I. P. R. 4 - Session I05
Wednesday, July 15, PM 13:40-17:20
Room 200
Polarimetry In Multi-Sensor Signature Fusion

Organisers : A.J. Bedard, Jr, and W.M. Boerner
Chairs : A.J. Bedard, Jr, and H. Schimpf

Recent Advances in Infrasonic and Near Infrasonic Atmospheric Sounding and Imaging

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Infrasound is radiated by a variety of geophysical processes including earthquakes, severe weather, volcanic activity, geomagnetic activity, ocean waves, avalanches, turbulence aloft, and meteors. The general properties of these signals are described in the context of the measurement challenges presented in detecting them. A brief history provides background concerning the evolution of infrasonic detection technology. Recent improvements in both hardware and processing software have made passive detection and identification of infrasonic sources on a continuous basis practical and should lead to valuable operational applications.. These hardware and software advances will be described with examples. The detection of meteors, meteorites, and space debris is an area reviewed to indicate the capabilities and uses of infrasonic observing systems. The fact that infrasonic systems together with seismic, hydroacoustic, and radionuclide systems are planned for the International Monitoring System offers wide opportunities for future synergistic research and some of these are indicated. Finally, potentially valuable geophysical applications are summarized.

Infrasonic Observation of Earthquakes

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Earthquakes generate infrasonic signals through their strong surface motions. These signals can propagate to large distances--hundreds or thousands of kilometers--depending upon the earthquake magnitude and propagation conditions. The long-range propagation of the signals depends upon the multiple bounce refraction and reflection between the stratospheric layers of the atmosphere and the earth's surface. Signals are detected primarily in the 0.5 Hz to 3 Hz frequency domain. The signal durations can be rather long, lasting many minutes and in extreme cases up to about one-half hour. The durations generally are strongly correlated with seismic magnitude.

A large number of earthquakes have now been observed at arrays of infrasonic detectors located at several sites and operated by this laboratory. Using beam-forming techniques the azimuth of arrival of the signals can be determined among other things. Generally the azimuths agree well with the seismic epicenters of the associated earthquakes. Other observed parameters are consistent with the pure acoustic propagation described above for the peak signals. In some cases signals are also observed which are related to the arrival of seismic surface waves at an array.

For several earthquakes of large seismic magnitude the signals appear to originate from regions at large distances from the epicenter in addition to the signal from the epicenter. We believe that these signals from extended sources are due to seismic-acoustic coupling in which the remote source is coupled to the epicenter by seismic surface waves; the remote source then radiates infrasound which propagates acoustically through the usual bounce mechanism.

We have found a well defined linear relation between the logarithmic normalized infrasonic amplitudes of earthquakes and their seismic magnitudes. The relation can be understood in an approximate way by the source physics. This relationship can be used to predict the detecibility of infrasonic earthquake signals.

The proposed global array of infrasonic arrays as part of the International Monitoring System of the Comprehensive Test Ban Treaty should be able to observe many earthquake occurrences. Several of the monitoring stations will be relatively close to zones of high seismic activity. Detections by multiple arrays will permit triangulation of the source regions. Synergism between seismic and infrasonic detections may provide enhanced physical information on the surface motion of earthquakes.

Recent Advances in ULF/ELF Polarimetry : Special Fusion of ULF/ELF with VHF/UHF Signatures for Geo-Environmental Stress Change Monitoring

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The NAV-SPAWAR (formerly NCCOSC or NOSC), RDT&E Division (ULF)/ELF Communications Section developed and operated the Low Frequency Polarimetric ULF/ELF Signature Observatory on Point Loma Seaside in San Diego CA since 1990. The Low Frequency Observatory records ELF signals with *'3-axis search coil magnetometers'* for which the instrument self-noise levels are at least 6dB below the average environmental ELF background levels. The main magnetometer station is located at the NAV-SPAWAR point Loma Sea-side facility, and two remote observing stations are located and operated at the SCRIPPS Pinon Flat Geophysical Observatory and the former NOSC La Porta Radio Observatory sites, all including, in addition to 3-axis search coil magnetometers, also north-south and east-west printed ground probes for measuring self-potential and signal-induced currents, and also a vertical electric field sensor for measuring low frequency changes in the vertical electric field with measurements taken within the .1(.05) to 20(100)Hz ranges, respectively.

Studying the polarization of radio waves in the ULF/ELF frequencies provides additional information concerning the sources. Briefly, the following characteristics are known of polarized waves within Southwestern California : (i) Waves of storm origin are predominately polarized in the north-south direction as defined by the magnetic component. (ii) The associated electric component of these waves would the polarized in the east-west direction . (iii) Non-storm sources will tend to generate waves with random polarization. (iv) Communications signals are predominately polarized north-south. (v) Circular and elliptical polarization are found in waves derived from the magnetosphere. (vi) The magnetic and electric components are out of phase. The phase difference can be used to estimate source distance. (vii) The polarization can be used to estimate direction of source. (viii) In general, the vertical component will be small. (ix) Large vertical magnetic components imply local sources (i.e., 0 to several hundred kilometers). (x) Local sources also generate components in the horizontal direction. (xi) Underground sources almost always generate magnetic fields but not electric fields as detectable on the surface. (xii) The original polarization can be distorted by local topology and mineral content. These listed characteristics have been used to help in identifying local to distant to far-distant sources in the low frequency regime.

In the high frequency regime, recent advances in SAR (Synthetic Aperture Radar) imaging has enabled scientists to generate images of strained faulted zones. The images were generated by combining pixel data obtained from a number of passes over the target area by an aircraft or satellite. The coherent combining of these pixels results in an interferogram which show clearly the overall strain patterns. Unfortunately, as of now, images can be generated only after large earth movement (i.e. earthquake). It is anticipated that further development in the RP-UWB-POL-D-InSAR technology will enable pre-quake patterns to be imaged.

Correlation between ULF/ELF co-seismogenic signatures with repeat-orbit InSAR image overlay interferograms will be presented in order to demonstrate the potential of fusing multiband ULF/ELF with VHF/ULF spectral data i ngeo-environmental stress change monitoring.

Low Frequency Atmospheric Acoustic Energy Associated With Severe Weather Vorticity

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An infrasonic observatory co-located with the Colorado State University CHILL radar during the summer of 1995 permitted unique comparisons between severe storm dynamics and detected acoustic energy at sub-audible frequencies near 1 Hz. Radar observations of a velocity couplet (interpreted as a mesocyclone) showed a circulation maximum descending over about 30 minutes while moving to the east. Acoustic energy detected correlated well with these observations. A model of sound radiated from vortex systems predicts frequencies in the range observed. These data are interpreted in the light of past infrasonic observations and implications for detection and warning discussed. An ongoing study comparing regional tornado and funnel sightings with archived infrasonic data has identified 9 cases to date where the infrasonic signals occurred at the time and from direction of the vortices.

For some of these cases the distances were greater than 100 kilometers. We propose to design and operate a rapid deployment infrasonic observatory and operate the system over a broad frequency range to obtain "voice prints" of a number of mesocyclones and tornadoes and evaluate the technique as a method of improving short term warnings. Other tornado detection and warning approaches will also be discussed (e.g. seismic and electromagnetic). Finally, opportunities for studying other geophysical sources of infrasound will be reviewed. These include infrasound associated with earthquakes, avalanches, ocean waves, and meteors. There are many possible opportunities for comparative studies with a range of remote sensors and several of these will be outlined.

3-Dimensional Polarimetric Imaging of Metallic Objects in Snowpack Using an FM-CW SAR

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The FM-CW radar is suitable for short range sensing. Since the L-band frequency can penetrate into wet snowpack, we employed the L-band (1.1-2.2 GHz) in our polarimetric FM-CW radar system to detect objects in snowpack of 280 cm deep. This paper presents the fundamental experimental polarimetric detection results of two metallic bars buried in the snowpack, which were carried out on Feb.1-2, 1997 at Yamakoshi village, Niigata Prefecture, Japan. Snowpack usually consists horizontal snow layers such as new snow, dry snow, fine grained snow and depth hoar layer, etc. Two metallic bars were inserted into the snowpack horizontally with approximately 45 and 135 degrees oriented each other so that polarimetric response comes out significantly. One of the bars is a long circular cylinder of 3 cm diameter, the other is L-shaped (with each side 4 cm) and 180 cm long, which were buried at the depth of 60 cm and 110 cm, respectively. The transmitting and receiving horn antennas were scanned 2 dimensionally on the snow surface. This scanning produces 3-D images of snowpack structure. The measurement was conducted on HH, HV, and VV polarization combination. After obtaining full polarimetric data, it is possible to create any polarization images within the medium. In the presentation, we present Co-Pol max, Co-Pol null, Span and other polarimetric filtered images. Along with these images, we tried to decompose these targets using 3-component decomposition algorithm proposed by E. Krogager. Some decomposition results and the problems associated with inhomogeneous medium and target size versus wavelength will be given.

Automatic Target Recognition with a Two-frequency Millimeter Wave SAR

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In the framework of a multi-national NATO measurement campaign,airborne measurements with the FGAN `MEMPHIS' two frequency SAR sensor system, operated simultaneously at 35 GHz and 94 GHz with boresighted antennas, were performed over an ensemble of five different relocatable military high value targets embedded in a mixed clutter background. Both radar systems are fully polarimetric receiving two orthogonal polarizations simultaneously. Moreover, the 35 GHz radar is able to switch the transmit polarization from pulse to pulse thus providing the full scattering matrix. Either linear or circular transmit polarization can be selected.

These data are supplemented by ISAR tower/turntable data of one of these five targets („T1"), taken by the fully polarimetric ARL high resolution radar under the same depression angles and at the same frequencies over the full 360 degree range of aspect angles.

Based on these measurements it is analysed how a combination of several polarimetric channels of one or two frequencies can be combined to construct features for the discrimination of T1 against the other four targets. A statistical analysis is carried out to examine the degree of statistical independence of all channels used, and to decide which combination of channels carries the maximum information.

As in realistic applications the orientation of the targets under consideration is not known, unless determined by a separate algorithm, the feature references have to be determined as a function of aspect angle. Accordingly also the distance in feature space which tells whether the other targets or any clutter discretes are likely to be taken as T1, can be determined as a function of aspect angle. The area surrounding the target site is large enough to provide a satisfactory estimate of the false alarm density.

Road Surface Condition Observed by Polarization Ratio Using a Bi-static FM-CW Radar

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This paper presents the material constant (permittivity and conductivity) of ground medium observed by a polarimetric FM-CW radar. The ground is assumed to have a flat surface and to be a lossy dielectric half space medium. The material constant of road surface is affected by moisture content and temperature, i.e., wet by rain, dry, or snow-, sleet-, ice-covered, etc. The purpose is to measure the road surface condition by using a polarimetric radar for safe vehicle transportation. Using a simple ku-band bistatic FM-CW radar system, the polarization ratio of reflected signal from the ground surface is measured, which determines the material constant or road condition. The main feature of the system is to use 45 degree oriented transmitting antenna only. The reflected signal is picked up by two polarimetric orthogonal antennas consisting of vertical and horizontal horns which yields the polarization ratio of the reflected wave. If the incidence angle upon the surface is set near the Brewster angle, the polarization ratio changes significantly with the material constants. This orientation angle is important factor for a simple hardware realization. Assuming the normal asphalt and concrete surface, a theoretical polarization ratio, ellipticity and tilt angles are derived based on the classical Fresnel reflection coefficient formulation. The polarimetric calibration is conducted by using a metallic flat surface, because the polarization ratio is unity for wide metallic plate reflection. Then, some measurements were conducted to show the validity. The measurement results are compared with the theoretical data. The surface condition (including wet, dry, or asphalt, and concrete) is well detected by the proposed method in real time.

Reference

N. Kees, J. Detlefsen, "Road surface classification by using a polarimetric coherent radar module at millimeter waves," 1994 IEEE National Telesystems Conf., pp.95-98, 1994.

Object Classification in Traffic Environment using Polarimetry

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Progress in technology of millimeter wave components together with decreasing prices makes radar operating in those frequency ranges a very interesting sensor solution even for automotive applications. Great efforts have been made in the past to realize prototypes of driver-assistance-, intelligent-cruise-control- and collision-avoidance systems. Those systems must be able to detect obstacles with high reliability independent of weather conditions to improve comfort and safety for all road users.

Common radar systems are only capable of detecting objects, but are not able to distinguish between different classes. Especially in traffic scenarios the ability of classifying obstacles would be very helpful. An example for the problems such a system has to cope with is a tree or bush located near the roadside, particularly if the road is winding. For this reason a radar with the capability to recognize different kinds of possible obstacles could decrease the false alarm rate of the system.

A fully polarimetric instrumentation radar, based on ready-made components, was used to investigate the specific conditions in road traffic environment. Using this real aperture imaging system we obtained several spatial data sets of road scenarios. Each voxel of this so called radar data cube is represented by the full scattering matrix. For visualization purposes a tool called PPDVIS (Planar Polarimetric Data VISualization) was developed. The features provided by this software package are briefly introduced in this paper.

To select the scattering matrices of a single target object a detection algorithm based on RCS top projections of the radar data cube is used. Several target decomposition methods were applied on the data. A neural network was chosen to meet the requirement for automatic target classification. Statistical approaches like the degree of polarization are investigated and the results are presented.

Session J05
Wednesday, July 15, PM 13:40-15:00
Room 450
Dielectric Characteristics of Geophysical Media

Organiser : M. Hallikainen
Chair : M. Hallikainen

Dielectric Properties of Wet Snow in the 0.1 to 37 GHz Range

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The dielectric properties of liquid water and the geometry of the ice-water-air system determine the permittivity of wet snow. It has been previously verified experimentally that the permittivity of wet snow is a compressed version of liquid water, exhibiting practically the same relaxation frequency as that of water at 0°C. No single experimental data set exists that covers the entire frequency range of 0.1 to 37 GHz. The most extensive data set covers frequencies between 3 and 37 GHz [1]. Additional data sets cover frequencies between 4 and 12 GHz GHz [2] and around 1 GHz [3].

In this paper, we present numerical equations that cover the 0.1 to 37 GHz frequency range. Separate equations are presented for the real and imaginary parts of the complex permittivity. The results are compared against existing experimental data. The main advantage of the new results is continuous coverage of the UHF and microwave frequency ranges used for remote sensing of snow.

References

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[2] Linlor, W. I., Permittivity and attenuation of wet snow between 4 and 12 GHz, J. Appl. Phys., vol. 51, no. 5, pp. 2811-2816, May 1980.

[3] Tiuri, M., A. Sihvola, E. Nyfors, and M.T. Hallikainen, The complex dielectric constant of snow at microwave frequencies, IEEE J. Oceanic Engineering, OE-9, 377-382, 1984.

A Comparison of Dielectric Models of Dry Snow

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The objective of this study is to examine the range of validity of strong fluctuation theory models for dry snow dielectric constant. Two strong fluctuation theory models are used : low frequency model presented by Tsang et al. (*1982*) and general model presented by Stogryn (1984). A spherical symmetric correlation function was used in this study. The effective permittivity as a function of mean grain size, frequency and temperature are numerically evaluated. It is shown that these two models have some difference even at low frequency, especially for large mean grain size. One interesting discovery is that the imaginary part of effective permittivity of snow may be large than that of ice particles. At high frequency, the difference may be more than 100 times. This is an impractical result. Thus more accurate dielectric models of dry snow are expected.

Several empirical and theoretical mixing models for dry snow are also considered in this study. The select models are Hallikainen model (*Hallikainen et al. 1986*) and Mätzler model (*Mätzler 1987*) for real part of dielectric constant, and Tiuri model (*Tiuri et al. 1984*), PVS model and Tinga model for dielectric loss factor. These models are limited to the low-frequency approximation for which the effects of scattering were neglected. This limitation means that dielectric constant is not dependent on grain size. It is also shown that under low frequency limit, the zeroth-order approximation of the effective permittivity ε_g in strong fluctuation theory is identical to the PVS model.

Microwave Dielectric Characterization of Vegetation

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Measurements of the complex permittivity of vegetation, such as trees, have been performed in the microwave range with an open-ended coaxial probe reflection technique. For trunks and branches, measurements were performed with the probe oriented along different orthogonal stem directions and at different radial depths into the wood. The anisotropy of wood dielectric properties will be illustrated with measurements that show that the longitudinal or axial component, i.e. the component parallel to the wood grain, is roughly 1.5 to 3 times as high as the transverse component. This may have an impact on the development of vegetation scattering models.

Open-ended coaxial probe techniques have been used by several workers to measure the dielectric properties of living trees. The sensitivity and validity range of these techniques depend on the probe dimensions and on the model relation which is used to derive the complex permittivity of the test sample from the reflection coefficient measurements. In this work, a rational function model, recently developed by Stuchly *et. al.* (*IEEE Trans. MTT*, Febr. 1994), was used for the probe tip aperture admittance. The coefficients of this model, published by Anderson *et. al.* (*IEEE Trans. MTT*, Febr. 1994), were derived by a fit to moment method full-wave simulations, such that radiation effects, energy storage in the near field and the evanescent waveguide modes are taken into account. With this model it is possible to obtain sufficiently accurate results for the dielectric constant and loss factor in the ranges [1-80] and [0-80] respectively, which cover the dielectric properties of vegetation. Furthermore, calibration of the measurement set-up with reference liquids is not necessary, if the time gating feature of the Network Analyzer is used. The method has been validated on known materials and is compared with a method which uses a simple lumped capacitance model for the probe tip.

In vivo Dielectric Response as Related to Tissue Structure, Function and Physiologic Activity in Selected Trees

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The dielectric properties of vegetation tissue are an integral component to the coupling of electromagnetic properties of a vegetation canopy and its physical properties. Understanding the dielectric behavior of vegetation is important (1) for establishing the connection to and allowing the interpretation of microwave remote sensing signatures of vegetated terrain and (2) as a tool to assist in monitoring and interpretation of the physiological processes within vegetation tissues.

In this paper, we present a series of in vivo dielectric measurements performed on several trees from selected zonobiomes under varying growth conditions and during various times of the growing season. Measurement series have been conducted with equipment designed to provide consistent and continuous in situ monitoring of the dielectric response of several woody vegetation components in a near simultaneous fashion. As vegetation species vary widely with respect to the structure and spatial distribution of hydroconductive tissues, we show that dielectric constant can be useful for characterization of the spatial distribution of phloem, xylem, and heartwood. Dielectric response to short-term and seasonal variations in hydrologic parameters are examined. We present a review of short term and seasonal dielectric response of trees influenced by a variety of growth conditions and meteorological parameters. Finally, we present an examination of temporal dielectric response as a function of position with single individuals.

The in situ data demonstrate that although a direct correlation between dielectric constant and the tissue hydroconductive structure may be inferred, the temporal response of dielectric constant is highly complex and time variant. Interpretation of the temporal behavior requires an understanding of the plant's hydrologic and chemical state. Understanding the physical processes that govern a plant's dielectric behavior may allow characterization of plant physiology from in vivo observation of vegetation dielectric constant.

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract to the National Aeronautics and Space Administration, and at the Department of Plant Ecology, University of Bayreuth, Germany.

Session J06
Wednesday, July 15, PM 15:00-17:40
Room 450
Microwave Remote Sensing of Crops

Organiser : P. Ferrazzoli
Chairs : P. Ferrazoli, J.-P. Wigneron

The Relations Between Backscattering Coefficient and Biomass of Small Leaf and Wide Leaf Crops

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Much research has been carried out in recent years in studying the relationships between the backscattering coefficient at different frequencies and polarisations and the biomass of several crop types. By using AIRSAR and SIR-C/X-SAR data collected in 1991 and 1994 on the agricultural test-site of Montespertoli (Italy), good correlation coefficients have been obtained for the relationships between backscattering coefficient at P, L and C-bands and the plant water content of agricultural crops and the woody volume of forests. These relations were notably improved after separating vegetation into homogeneous groups, characterised by scattering elements of similar dimensions and using observation frequencies whose wavelengths were in the same order of magnitude of the main scattering elements of plants.

Later on, a larger data base has been analysed, including EMISAR data collected on a Sweden test-site and ERS-1 and JERS-1 data on Montespertoli area. From the analysis of this data set which included observations on a wider range of crop types, two different behaviours have been observed. It has been confirmed that, in general, both L and C bands shows an increasing trend as the biomass of plants characterised by large leaves and thick cylinders increases (sunflower, corn). However, when plants identified by narrow leaves and relatively thin stems are considered (wheat and alfalfa), this trend tends to disappear at L-band and becomes decreasing at C-band. The same results have been obtained using ERS-1 SAR data at 23? incidence angle as well.

In order to interpret these two opposite behaviours, characterised by a dominance of absorption in one case and of scattering in the other one, a semi-empirical model based on the crop geometrical characteristics has been carried out and compared with experimental data. Since the shape of leaves seems to have a great influence on the backscattering coefficients, they have been considered as composed by disks or ellipses and the ratio between their length and width has been used in the model. Although based on empirical observations, the model seems to be able to predict the different trends of the backscattering coefficient as a function of biomass for different plant geometry.

Using Radiative Transfer Models with Measurements of Crop Structure to Explain ERS Signatures

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Throughout the 1997 growing season, we conducted a sequence of intensive crop structural measurements in the area of Driffield, UK, timed to coincide with the 35-day ERS-2 overpasses. The measurements were carried out in twelve fields, three for each of four different crops: winter wheat, spring barley, oil-seed rape and potato.

The crop measurements included quantitative determinations of the spatial densities, physical dimensions, orientations and moisture contents of all the major plant components, together with an assessment of the soil surface topographies and moisture contents. From ERS-2 images, field averaged backscatter values have been extracted by NRSCL, UK, to give temporal signatures covering a contemporaneous period for the fields under study.

We are using input parameters derived from the crop datasets to drive radiative transfer models : *RT2* (GEC-Marconi), a second-order model, and *Mimics* (University of Michigan). Uncertainties in the predicted signals have been incorporated to allow a direct comparison of the C-band, vertical polarisation, simulations with the ERS temporal signatures. In this way we make clear the degree of reliance we can place on the model predictions.

The models are used to investigate the physical reasons for the observed temporal signatures and the marked differences observed between different crop types. This also allows a comparison of the two models and commentary on their relative merits. One of the major advantages of the RT2 model is that it can be used to describe cross-polarised scattering.

We will extend the results from the ERS-2 study to make predictions about the expected response of ENVISAT using both the polarisation and incidence angle versatility, with a view to quantifying the information gained about crops by this flexibility. Where possible, these inferences will be supported by measured values from airborne and ground-based measurements.

Monitoring Surface Variables Over Crop Fields from C-Band Radar Data

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In this work, a discrete physical model is used to analyse radar data sensitivity to the land surface parameters over vegetation canopies. The analysis is based on C-band radar data measured over a soybean crop during the whole vegetation cycle at two incidence angles: 15 and 23 degrees. The measurements were acquired by the scatterometer Ramses, designed by CNES (Centre National d'Etudes Spatiales), which was mounted on the mobile platform of a crane boom. The experiment took place in 1989 at the INRA Avignon remote sensing test site. The unique characteristics of this data set made it a very valuable tool to analyse the radar measurement sensitivity to land surface variables of interest (in particular, soil moisture and vegetation biomass) :

- the 90-day measurement period allowed to monitor large changes in vegetation biomass, in relation with vegetation growth / maturity / senescence of the crop canopy.
- very contrasted soil moisture status were obtained during the whole measurement period, from both irrigation and rainfall events
- intensive soil and vegetation ground data were measured and provide an exhaustive description of the soil, vegetation and hydrologic characteristics during the whole experiment.

A two-step analysis is carried out in this work: first, the SOYBEAN 1989 data set is used to calibrate a discrete physical model; second, model simulations are carried out to investigate further the radar sensitivity to the surface variables over agricultural fields. The model is based on radiative transfer equations and on a "discrete" description of the canopy layer. Scattering phase matrices for discs (leaves) and cylinders (stems and petioles) are based on the works of Karam et al. (1992).

A simple inversion approach is used to retrieve surface soil moisture wg (m^3/m^3) during the whole crop cycle. The uncertainty on the wg estimates is lower than 0.05 m^3/m^3. However, a thorough analysis of the inversion process shows that the retrieved data are very sensitive to the estimates of the vegetation characteristics and of the soil roughness effects. In particular, a complete sensitivity analysis of vegetation input data is made and provides useful material to evaluate the uncertainty of retrieved estimates obtained from radar remote sensing data.

On the Use of RADARSAT and ERS SAR Data for Ricefields Monitoring

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In the past few years, the possibilities for monitoring rice crops using multitemporal ERS data have been assessed at several places throughout the world.The radar backscatter of flooded ricefields at C-band, VV, 23 degrees of incidence, has been found to increase significantly during the crop cycle, from sowing to harvest.

Recently, RADARSAT data have been available at C-band, HH polarisation, and multiple incidence angles. Since the rice canopies are characterised by the plants, with quasi vertical structure, over a water surface, differences in polarisation behaviour are expected between the backscatter from ERS and RADARSAT data. Also,the incidence behaviour of RADARSAT data at different modes needs to be investigated. The results will have an impact on the algorithms to be developed to map and monitor rice fields.

In this paper, RADARSAT data acquired over a test site in Java, Indonesia at several dates in 1996 and early 1997 are analysed. In addition, one ERS image acquired at one of the dates has been analysed for comparison purposes. Ground data have been collected at the different SAR acquisition dates . The backscatter coefficients extracted from SAR data are expressed as a function of the plant age and plant biomass. The temporal variation of the RADARSAT backscatter coefficients at the test site was found to be significant, but not exceeding 6-7 dB at the standard mode, 23 degrees of incidence. Lower temporal change, not exceeding 4 dB, has been found at the fine resolution mode, at 42 degrees of incidence .

The measurements have been interpreted using a theoretical scattering model based on Monte Carlo simulations of the scattering from an ensemble of scatterers which represent stems and leaves of rice plants. The polarisation and incidence behaviour of the backscatter are explained by the differences in wave attenuation and in the wave-plant-water interaction. Simulations studies are performed to assess the effect of different cultural practices, plant varieties and irrigation conditions. The results will be used to define the optimum method, in terms of the SAR data, the acquisition dates, the SAR image analysis technique, to map and monitor rice fields using RADARSAT, ERS, and the forthcoming ENVISAT data.

Multifrequency Emission of Wheat : Model Validation and Application to Parameter Retrieval

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In summer 1993 extensive measurements were carried out over agricultural fields at the INRA test site, located near Avignon, France. The PORTOS radiometer, operating at 6 frequencies (1.4 GHz, 5.05 GHz, 10.65 GHz, 23.8GHz, 36.5 GHz and 90 GHz) was used to collect data at several observation angles and at both polarizations (H and V). In particular, a wheat field was observed during the whole cycle, from DoY 109 to DoY 189; simultaneously to radiometric measurements, all the significant biophysical and geometrical parameters were monitored. The results of this campaign, due to their extension and completeness, form an ideal basis to refine and validate physical models; moreover, they allow to deeply investigate the potential of passive microwave systems in the retrieval of fundamental parameters, like biomass and soil moisture.

In this work, wheat emission has been simulated using the microwave vegetation model developed at Tor Vergata University, which is based on the Radiative Transfer theory and describes vegetation as a layer filled with discrete elements, having shape of discs and cylinders, over a half space with rough interface. The model can represent several kinds of vegetation due to its flexibility, since dimensions, orientation and location of the elements may be selected in order to give a realistic representation of the crop geometry. For wheat, we have considered an upper layer filled with near-vertical cylinders and discs (ears and leaves) and a lower layer filled with near-vertical thin cylinders (stems). In order to simulate the emission during the whole crop cycle, different sets of input data have been associated to the various days of the year, on the basis of the measured ground-truth. Model simulations have been carried out at the five lower frequencies, at all observation angles and at both H and V polarization. A good agreement between simulated data and experimental data has been observed at all frequencies and both polarizations, although a unique input data set has been adopted for each day; few observed discrepancies are critically discussed.

Once the model has been refined and validated, a systematic study has been carried out to investigate the correlations between the available radiometric parameters (emissivities, polarization indexes, frequency indexes) and important field parameters like biomass and soil moisture content. It is shown that the availability of simulated data allows to draw conclusions more reliable than those attainable by uniquely considering experimental data. Finally, it is shown that a multifrequency radiometer allows retrieval of soil moisture, during the whole crop cycle, with good accuracy.

The Calibrated Radarsat Data for Rice Growth Stage Monitoring

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Remote Sensing technology has been applied to crop yield forecasting in Europe and north America for many years. It has been successfully used for wheat yield estimation in north China since 70's. But for rice monitoring, it is limited by the optical remote sensing data availability. Rice is the staple food in China and in many Asian countries as well. However, most of the rice growing areas are located in south of China. There are very cloudy and rainy. The visibility of synthetic aperture radar (SAR) seeing through cloud make SAR data a practical information source for rice monitoring.

This paper presents rice monitoring study in Zhaoqing test site of south China. Eight scenes of calibrated Radarsat images were collected for this study from April to end of July in 1997. The structure parameters of rice such as leaf width, leaf length and leaf height, orientation angle, etc. were measured in the selected paddy field. The backscatter coefficients are exacted from the calibrated Radarsat image acquired over the whole growing period of the early season rice. The variations of the backscatter coefficients reflect the different type of rice or rice in different growing stage. The study shows that the backscatter coefficients of rice is highly related to the height of the rice and Radarsat is an efficient tool for rice monitoring.

Soil Moisture Estimation Under Crops During a Vegetation Cycle

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Numerous studies demonstrated that microwave measurements, such as ERS1&2 images, can provide soil moisture index. On bare soil, soil moisture could be related to backscattering signal with a linear relation. Radar signal backscattered by canopy include, in addition to the soil contribution, a vegetation term which depends on crop parameters (water content, plant geometry,...). It reduces the sensitivity between radar signal and soil moisture. We propose, in the presented study, to determine, for the land cover type identified on the Pilot watershed (Orgeval, France), the vegetation and the corresponding period for which soil moisture could be derived with accuracy from ERS1&2 data. This approach has been assessed on two vegetation cycles (1995-96, 1996-97) using ERS1&2 multitemporal series, LandSAT data and terrain measurements on test fields (for soil: moisture and roughness, for plants: phenological stage, height, density and structure).

To identify land cover types present on the Orgeval site, ERS multitemporal series and LandSAT multispectral data are used to perform unsupervised classification. For each vegetation cycle, a crop mapping of the whole watershed area has been obtained. We focus on the case of winter wheat which is an important part of the cathment crops. Using a first-order radiative transfert model derived from Karam and Fung, the wheat canopy is modeled as a half space containing orientated elliptic disc-shaped leaves and cylindrical-shaped stalk. Scatterer dimensions and orientations are fitted to Orgeval data base. From the model, the vegetation contribution to the radar signal could be separated in two cases. From March to April and in July after senescence, the vegetation and soil contribution are of the same magnitude and the plant influence can be corrected. Formulation are proposed and compared with previous radar campaigns. From May to June, the soil contribution remains negligible and no soil information can be obtained. These results are confirmed by ERS/SAR data (averaged over wheat canopies on the watershed) during the two vegetation cycles. For other land cover types (corn and peas crops), ERS/SAR measurements are only used during bare soil periods to derived soil moisture. Considering comparable soil roughnesses, we determine an Ideal Soil linear Relation (ISR) between the radar signal averaged over bare soils and the soil moisture. By this methode, soil moisture mapping, at the watershed scale, are derived used the ISR with correction of the vegetation contribution if needed. At the watershed scale, efficient global soil moisture indexes are obtained for each ERS acquisition during the two studied seasons. They would be used to improve monitoring of hydrological cathments models.

Session K05
Wednesday, July 15, PM 13:40-17:40
Room J
Interferometry

Chairs : H. Zebker, U. Wegmuller

Large Scale Interferometric DEM and Map Generation Using ERS Tandem Data

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The generation of digital elevation models by means of interferometric processing of SAR data has been established as a well-known technique in recent years. Especially the theoretical background and its algorithmical implementation issues have been thoroughly discussed and are still subject to further investigations (e.g. phase unwrapping). This paper is devoted to the applicability aspect of the methodology, particularly regarding the construction of large area terrain models and landuse maps. A DEM of the entire Czech Republic, covering an area of about 80,000 km^2, was generated using data of the Tandem period of the ERS Satellites. The data were selected from a total of 10 ERS tracks (3 frames each) with various acquisition dates and baseline configuration parameters. The following subjects are discussed in detail :

- Single DEM generation (processor design, data selection)
- Mosaicking of frames within a track
- Mosaicking of tracks
- Error budget, including a study of baseline errors and atmospheric artifacts
- Operationality aspects of the InSAR technique for large area DEM generation

For a part of the investigated area a photgrammetric digital elevation model was made available which has been used for valdation purposes.

The elevation data were used to generate terrain geocoded SAR magnitude and coherence mosaics of the entire area. Using 3 amplitude layers of different seasons together with the interferometric coherence information, a total of 8 different landuse classes were seperated on the basis of neural network classification.

Land Subsidence Mapping with ERS SAR Interferometry

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In the frame work of ESA's Data User Programme, Gamma Remote Sensing addresses the use of differential SAR interferometry to map subsidence in urban environment. In urban areas man-made constructions contribute strongly to the backscattering. Due to the temporal stability of these scatterers the degree of coherence is high even for interferometric pairs with very long acquisition time intervals. As a consequence repeat-pass space-borne SAR interferometry allows the mapping of coherent displacement in the cm/year range. In our project we focus on the mapping of land subsidence in the Po river valley.

Land subsidence has been known in the Po river valley for several centuries. Today subsidence is especially occurring in the eastern part of the valley. The observed subsidence is a combination of natural and man-induced subsidence mainly from ground-water withdrawal. Land subsidence causes mainly two problems:

- Spatially heterogeneous subsidence in urban areas produces damages in buildings and working problems to hydraulic territorial systems in reclaimed lands. As a consequence the spatial gradient of the subsidence velocity is a very important parameter.

- Uniform subsidence of areas which are below or close to sea level, in combination with eustatic sea level rise, seriously endangers the hydraulic safety. In the Po river valley parts of the eastern territories lie completely below sea level and are protected by kilometers of embankments. The ground level at the historic center of Venice is only between 0.7 and 1.0 m above mean sea level. Even a few cm of ground surface lowering may contribute to the destabilization of the littoral zone.

The selected approach, the potential and the limitations of the technique will be discussed.

Calibration of Interferometric SAR System Using Kinematic Ground GPS Measurements

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The calibration of Interferometric SAR (IFSAR) systems based on using corner reflectors as ground control points, for missions that are extended over long time periods, or for global coverage missions like the forthcoming NASA/NIMA Shuttle Radar Topography Mission (SRTM), is not feasible due to cost or deployment constraints. In this paper, we present an alternate technique, based on the use of GPS surveys, which can be acquired at low cost over extended areas. The GPS measurements along radar identifiable features may be acquired and archived prior to any data collection and then used independently or in conjunction with other ground control data, such as known ocean surface elevation, in system calibration.

In this paper, we present an algorithm for the automated matching of the three-dimensional curve defined by the GPS transect measurements to its corresponding feature in the radar image and IFSAR derived height map. The estimated shift is fed back to a tuning algorithm in which system parameters are updated. This process may be iterated until convergence to the IFSAR calibration parameters is achieved. Unlike corner reflectors which are extremely compact and bright, roads are wide and often not easily distinguishable from their background. The lack of a strong contrast between the road and the background in the radar image and its variable width pose the main difficulties that need to be overcome. We present a technique to detect a road based on its statistical differences from its background, and discuss the issues related to the robustness of the technique and its limitations. As a practical demonstration, we present results for the calibration of the JPL TOPSAR system, as well as simulated results analyzing the expected performance for the forthcoming SRTM instrument.

Correcting Motion Compensation Induced Height Errors in Airborne SAR-Interferometry

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Airborne SAR interferometry has become a powerful technique for generation of digital elevation models (DEMs). The possibility to fly such systems on small aircrafts at low altitudes makes the mapping extremly cost efficient. Nevertheless, small aircrafts are affected by extreme motion errors as displacements of several tens of meters from the desired track or aircraft roll variations of several degrees. These variations are accounted for during the motion compensation steps of the processing. But for a full correction of these effects the topography of the mapped terrain must be known which in general is not the case and flat terrain at some reference level must be assumed.

This contribution suggests a post processing correction algorithm which can be applied iteratively after the image pair has been processed with motion compensation assuming flat terrain. Thereby a first estimate of the terrain topography is used to derive a height correction matrix so that the initial topography can be corrected. The new topography matrix can be used to calculate a second order correction matrix which in general can be neglected. The same procedure can be applied to the position matrices.

The E-SAR system of DLR is flying on a DO-228 aircraft at altitudes of about 3000 m above ground and thus is suitable to demonstrate the performance of the proposed algorithm. An interferometric single-pass scene from the Mt Etna campaign was selected showing height variations of about 700 meters. Motion compensation induced height errors in the order of 10 meters have been corrected using the proposed approach.

SAR Processing and Interferometry Software

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The main modules of our SAR processing and interferometry software are the Modular SAR Processor (MSP), the Interferometric SAR Processor (ISP), and the Differential Interferometry and Geocoding Module (DIFF&GEO).

The Modular SAR Processor (MSP) allows to process space-borne ERS, JERS, SIRC, and RADARSAT StripMap, as well as airborne SAR data. In the pre-processing step processing parameters are determined from the CEOS leader files and the raw data including Doppler ambiguity, and the Doppler centroid as a function of range. During range compression, data may be decimated in azimuth by prefiltering for the production of quick-look images of the scene. For JERS radio frequency interference (RFI) filtering is applied. The azimuth processor uses the range-Doppler algorithm with optional secondary range migration, as required for RADARSAT data. Deskewed and non-deskewed geometry are supported. The autofocus algorithm refines the along-track platform velocity estimate. The SAR processor is phase preserving and the processed images are radiometrically normalized for the antenna pattern, the along track gain variations of the radar, the length of the azimuth and range reference functions, and the slant range. The Interferometric SAR Processor (ISP) encompasses a full range of algorithms required to generate interferograms, coherence maps, and interferometric height maps. Two different algorithms to determine the registration offsets between an SLC image pair are used. The first one optimizes the real valued cross-correlation of the image intensities, the second one the magnitude of the complex cross-correlation, i.e. the fringe visibility. The interferogram generation includes common spectral band filtering. An initial baseline estimate is retrieved either form the orbit geometry or from the interferogram fringe frequency. Then, the flat Earth phase trend is removed and the degree of coherence is estimated. In preparation of the phase unwrapping adaptive filtering is applied. For the phase unwrapping a branch cut algorithm is used. Branch cuts are determined based on the residues, the coherence and a layover map. Prior to the height estimation the unwrapped the interferometric baselines estimation may be refined with ground control points. Finally, the estimated topographic heights are used for image rectification (to azimuth, ground range coordinates) and slope estimation. In differential interferometry the phase component originating from scene topography is estimated and subtracted from an interferogram. In order to optimize the flexibility the Differential Interferometry and Geocoding Module (DIFF&GEO) supports the 2-pass, 3-pass, 4-pass and complex interferogram combination approaches. In the 2-pass approach the topographic phase is estimated from a Digital Elevation Model (DEM), in the 3-pass and 4-pass approaches from an independent interferogram. A least squares error approach is used to optimize the scaling of the topographic phase, as an improvement over the scaling factor estimation from the baselines. As a part of the DIFF&GEO transformations between range-Doppler and map coordinates can be done. The geocoding can be based on a DEM in map coordinates or on interferometric height estimates. In order to automate the approach and to avoid the labor intensive selection of ground control points the refinement of the geocoding lookup table uses a cross-correlation approach between a simulated (based on the DEM) and a real SAR intensity image.

An Adaptive Least Squares Phase Unwrapping Algorithm

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SAR interferometry is beset by an essential problem: The determination of the absolute interferometric phase from only relative phase information. Noise in phase images reduces phase coherence, tends to corrupt fringe lines and produces phase residues, all of which lead to unwrapping errors. Low coherence arises from several additional sources: temporal scene decorrelation, image co-registration errors, interferometric baseline decorrelation, and scene dependent overlay and shadowing. Thus noise filtering and phase unwrapping are intrinsically connected. Here we present the phase unwrapping portion in detail. We have developed an adaptive phase unwrapping algorithm that optimally extracts the absolute interferometric phase from the relative phase via an adaptive weighted least-square method.

The heart of our approach is to recognize that the phase coherence is related to the local phase variance by the theoretical probability distribution function, and that the reciprocals of the variance can be employed to weight the phase unwrapping. Thus pixels in high coherence regions acquire greater importance than pixels in low coherence areas. Weighting the data in this manner optimizes the least square method. An immediate side benefit is the error estimate that the local variance provides.

Computationally, we employ an alternating direction implicit (ADI) method to calculate the unwrapped phases. The ADI method is a fast iterative computational algorithm that permits easy implementation of the realistic weight-maps, inclusion of elevation tie-points and relative weighting of *a priori* topographic information. The phase unwrapping problem does not have a unique answer and other unwrapping methods exist. Most of the alternatives require high phase coherence and relatively few phase residues in the interferometric image. These requirements are often met by heavy smoothing that reduces resolution or by masking which completely ignores low coherence areas. Masks of 1's and 0's have been employed; however, realistic weight maps have generally not been used.

Every least-square phase unwrapping method inherently underestimates slopes. Iterating the filtering and unwrapping procedure eliminates this systematic error. Our iteration procedure is to unwrap the filtered interferogram with the least-square algorithm generating an initial topography. The difference between this topographic phase and the original phase data is re-wrapped within the interval $[-\pi, \pi]$. Filtering and unwrapping this difference provides the first correction to the initial topography. Repeating these differencing, re-wrapping, filtering and unwrapping steps produces further topographic correction. Each of the subsequent phase differences to be filtered and unwrapped shows substantially fewer fringes greatly simplifying both the filtering and unwrapping procedures. Three or four iterations are typically sufficient to produce convergence.

In regions of high coherence, each iteration produces additional topographic detail. These details would be lost in unweighted least-square methods. In low coherence regions detailed, high-resolution topography is not possible ; however, best use of the available topographic information is made.

This iterative approach integrates noise filtering and unwrapping of interferometric phase images. Our adaptive, non-linear method preserves image resolution, detailed phase information and optimally incorporates low coherence phase information. We have tested our techniques on both simulated data and SIR-C/X-SAR imagery.

A New Algorithm for Fast and Stable Phase Unwrapping in SAR Interferometry Using Helmholtz' Equation Eigenfunctions and Regularization Procedure

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The paper addresses the problem of unwrapping of the interferometric phase (IF) produced in the SAR interferometry for the generation of high-precision terrain digital elevation models for geophysical, environmental and topographical applications. A new numerical method based on using the first Green's integral identity with properly chosen Green's function (GF) satisfying the imposed Newmann's boundary conditions is proposed and analyzed. In the developed method, the differential properties of the GF are instrumental in obtaining the ultimate solution to the considered problem. In the paper, the requirement of zero directional derivative on the boundary of the interferogram is imposed on the chosen GF in order to exclude the contour integration along the boundary of a region within which the unwrapped phase is sought for.

The chosen GF represents the linear combination of the two-dimensional Helmholtz' equation eigenfunctions which satisfy the Newmann's boundary conditions. The usage of the Helmholtz' equation eigenfunctions (being periodic functions for the rectangular IF support regions and more complicated functions for the others) ensures a computationally efficient analytical formulation for the unwrapped phase obtained using one- or two-dimensional fast Fourier transform algorithms.

The unwrapping algorithm is further elaborated using the developed method of adaptive (with respect to the phase noise level) regularization when searching for a gradient of the measured noisy IF. The regularization procedure essentially reduces to modification of the GF so that the usage of the modified GF leads to significant increase in both the accuracy and sensitivity of the phase unwrapping procedure. Thus, the developed method possesses not only high stability with respect to the propagation of the unwrapping error, as would be the case if the regularization procedure were not used, but also with respect to local perturbations in the unwrapped phase on account of locally distributed measurement errors.

To remove the bias inherent to phase unwrapping given the noisy initial data and to further increase the sensitivity and accuracy of the unwrapping procedure, the mean value and the variance of the difference between the noisy and true wrapped phases is computed in terms of the value of the true wrapped phase itself and the coherence between two corresponding SAR images. This computation, besides its usefulness for the regularization procedure, affirms that the noisy interferometric (wrapped) phase has the negative bias whose value strongly and in nonlinear manner depends on both the true wrapped phase and the coherence between the two SAR images corresponding to the specific point of the interferogram.

The developed interferometric phase unwrapping algorithm is applied to the real interferogram (with dimensions 256×256 pixels) of a region near Bern (Switzerland) registered by the radar of the satellite ERS-1 and supplied by CNES (Centre National d'Etudes Spatiales, Toulouse, France). The unwrapped phase is presented in the closed analytical form and is obtained numerically for less amount (in 10-20 times, depending on the specific numerical formulation of the developed unwrapping method and on the regularization mode) of computation time compared to that needed for the existing methods calling for the usage of the analogous mathematical background (e. g. the first Green's identity). Moreover, the developed regularization algorithm was shown to significantly increase the accuracy and sensitivity of the newly developed unwrapping procedure.

Multilook Processing of Interferometric SAR Imagery Using Discrete Wavelet Approximation

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The contribution of interferometric synthetic aperature radar (InSAR) to topographic mapping of surfaces promises a high resolution, globally consistent approach to generation of digital elevation models (DEM) and offers specific features which optical instruments cannot attain.

However, the effect of decorrelation in an interferometer increases the standard derivation of inferred phase estimates and hence error on the derived terrain height values. Therefore, InSAR data is frequently multilook processed for data compression and reduction of speckle. In this paper, we present two distinct implementation approaches of multilook processing. In the first case the phase difference can be derived from maximum likelihood distance estimates to achieve effective 4-look, 8-look, or 16-look processing. The second type of implementation, which we analyze here, is obtained by the discrete wavelet transform. Inferred phases in different number of looks can be effectively approached by wavelet approximations in different levels.

Particular applications of different wavelet functions are also presented and discussed in order to estimate their properties. The results of multilook processing of InSAR data have been provided to phase unwrapping procedures, which can remove the phase ambiguity and then make terrain maps. Finally, comparisons of various DEM maps using different multilook processes are made to measurements from ERS-1/2 Tandem and CV580 Airborne data of Taiwan.

Sensitivity Evaluation of the Multibase Interferometer

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The multibase interferometer with a linear phase array antenna is intended for measuring of one of the angular coordinates of a radio signal source, for example, azimuth. Phase systems allow to carry out measurements with high accuracy, however they have common fault: the ambiguity of phase definition on any measuring scale (phase is measured with accuracy up to an integer number of periods 2π repetition). There are effective algorithms of phase measurements ambiguity elimination based on share algorithmic processing of a measured phases differences collection. However these algorithms were developed in the supposition, that the distribution of phase errors on measuring bases is normal, and it is fair only for large signal-to-noise ratios **q** in at receiving channels (**q**>3). But very often there is a task of obtaining of high accuracy measurements in the radioengineering system working on far distance; for that it is necessary to estimate efficiency of existing algorithms at operation with weak signals (**q**<3). The given task is decided by dint of simulation on the computer of the phase error distribution in the most common case, when **q** value has no any limitations.

It is known that the distribution of a phase of additive mixture of a signal and noise in common case is the function of signal-to-noise ratio, and cannot be expressed through elementary functions. For simulation the distribution obtained by V. Cvetnov is used, where the phase error distribution is expressed through integrated L-functions. The given approximation is acceptable, since at $q \to 0$ the phase error distribution converges to the uniform one, and at $q \gg 3$, to the normal one. The simulation of the phase error distribution is produced by dint of programs realizing the Neumann method, which allows to get samples of random values with any distribution, if the graphics or analytical description of the distribution is known. The operation of the interferometer is simulated by programs developed in the Radioengineering Systems Department of Tomsk State University of Control Systems and Radioelectronics, which realize maximum verisimilitude (optimal) and quasioptimal algorithms of ambiguity elimination. The measuring bases are created so that the differences of phases are measured comparatively to the one common antenna element. Note that the way of a measuring bases construction unambiguous determines a structure of a phase errors correlation matrix in N receiving channels. In our case it is possible to set a normalized correlation matrix with relations: $R_{i,j} = 1$ at $i=j$, and $R_{i,j} = 0.5$ at $i \neq j$. The probability of the right elimination of ambiguity was adopted as a criterion of a system effectiveness. As a result of simulation the graphics dependencies of probability of right elimination of ambiguity as functions of a signal-noise ratio for number of bases 2...9 (for maximum verisimilitude (optimal) and quasioptimal algorithms) are obtained.

It is shown, that at operating with optimal algorithm while increasing of an number of measuring bases the ambiguity is eliminated at smaller values of a signal-noise ratio. Therefore, the phase system with a bigger number of measuring scales is more effective from a point of view of probability of right elimination of ambiguity. At operation with quasioptimal algorithm such strict dependence is not observed, and the system with some number of measuring scales differed from maximum will be more effective.

Thus the offered approach allows to estimate limiting sensitivity of phase systems working according to a principle of maximum verisimilitude, and efficiency of known algorithms at if a condition $q \gg 3$ is false.

Processing the Results of Synthetic Aperture Radar Interferometry by the Method of Maximum Likelyhood

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Images got in the process of synthetic aperture radar (SAR) measurements have one serious drawback - they don't give information about the project height. One of the ways to improve the situation is to carry out one base SAR measurements at several frequencies which practically corresponds to the measurements performed by a linear antenna grating with several phase-measuring baselines. We assume that all baselines are ambiguous. Phase errors are having zero middle values and are subordinated to the normal distribution. It is known their correlation between channels.

The paper is devoted to the improvement of the interferometer phase patterns processing which means measuring the object height using phase images got from the interferometer measurements at several frequencies simultaneously using the method of suggested algorithm allows to estimate the number of the phase shift full periods at all frequencies with high accuracy without preliminary signal processing. Such technique allows to shorten the time of the height estimation compared with the traditional methods of signal processing.

There are given results of numerical modeling of the upper and lower probability limits of the phase measurements ambiguity correct elimination for difference values of baselines and different values of phase errors. The functional structures of phase direction finder are made in according to the suggested algorithm.

The Usage of Multimeasure Spheres Packing of Multiscale Interferometries

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The phase directions finders with antenna system with linear or plane array structure that are intended accordingly for measurement of one or two angular coordinates of radio radiation source are considered. The directing cosines v, u of a signal source concerning axes of cartesian coordinates of the aerial of an array are defined on set of a difference of phases $\vec{\varphi}$, between its elements. We assume that all scales are ambiguous. Sources of errors of measurement are the phases errors in receiving measuring paths and on radio waves distribution line having normal distribution of probabilities, zero average meanings and known correlation matrix $\mathbf{B}_{\varphi}$. The directing cosines v, u are parameters of vector $\vec{\varphi}$ n-measure probabilities distribution, where n is a number of measured differences of phases. The estimations of v^* and u^* are found according to a principle of the maximal plausibility.

The purpose of the report is to find limiting ratios among the number of phase measuring bases, level of phase errors, probability of correct ambiguity elimination P_0 and accuracy of coordinates estimation in the situation of correct ambiguity elimination. On this basis two tasks are solved.

1. The account of limiting achievable probability of correct ambiguity elimination of at given phase measuring is based of demanded accuracy direction finding and correlation matrix of phase errors.

2. Second task is to estimate the affinity of certain antenna structures of phase direction finder to the ideal one.

As a criterion of affinity it is possible to accept the ratio $\nu_{n-r} = \dfrac{\delta_{n-r}}{\delta_{n-r,\max}} \le 1$, where δ_{n-r} is packing density of spherical surfaces of equal density distribution.

In the work are the results of accounts ν_{n-r} for the best out of phase direction finders linear structures that are known by the authors. The achieved meanings ν_{n-1} lay within the limits of 0.65-0.95.

Session L06
Wednesday, July 15, PM 13:40-16:00
Room R01
Wireless Sensor and Communications Techniques II

Organisers : A. Springer, R. Weigel

Chair : A. Springer

Site-Specific Propagation Modeling for Wireless Communication Systems

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Ray Tracing is a computational technique commonly used for site-specific propagation modeling. Received signal amplitude and phase at a particular point in space are determined from a physical model of scatterers in the propagation environment using quasi-optical techniques [1]. Advantages of ray tracing include 1) the ability to simultaneously determine both the stochastic nature of signal level variations and the time dispersive characteristics of a given propagation channel and 2) the increased accuracy that a site-specific calculation yields when compared with a purely statistical model. However, the approximation of the transmitted signal as a ray or system of rays can introduce significant error into the channel model when the carrier wavelength is of comparable size to local scatterers. This is an issue for indoor propagation modeling where important feature sizes may approach wavelength of operation. A full wave simulation technique such as the finite difference time domain method (FDTD) [2] does not suffer accuracy problems in this situation, but is, in general, prohibitively computationally intensive.

This paper addresses methods for increasing the accuracy of the ray tracing technique when the quasi-optical assumptions are not satisfied. To quantify and subsequently reduce the error in the ray tracing method, FDTD is combined with the Kirchoff Surface Integral Formulation [3] providing a very accurate portrait of the received signal. Use of the Kirchoff Surface Integral Formulation enables reduction of the size of the FDTD computational domain. As a result, grid dispersion is minimized and computational efficiency may be greatly increased for even moderately-sized computational domains. simulation results show how knowledge of the ratio of carrier wavelength to local scatterer dimension can be used to determine errors in wideband propagation measurements such as power delay profile. Information obtained from comparison of ray tracing to the full wave simulation is used to develop improved models for the ray tracing method. Applications to wireless communication systems including PCS will be shown.

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High Resolution Measurement Equipment for the Determination of Channel Impulse Responses for Indoor Mobile Communications

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The quality of the received signal in future mobile communication networks with high bitrates depends not only on the level but also on the delay spread of the signal. In this paper a new measurement equipment for the determination of the channel impulse response with a very high resolution of 5 ns is presented. It is based on the correlation of pseudo random binary sequences (PRBS) with a bitrate of more than $f_C = 250$ MBit/s. The channel sounder is mounted on a trolley and can be moved easily inside buildings. Many thousands of measurement points have been considered in different propagation scenarios. Even situations where transmitter and receiver are in different rooms and far away from each other are possible because no connection between transmitter and receiver is necessary and this is one of the main advantages compared to measurements performed with network analysers [1]. The principle of the idea realised is given in figure 1.

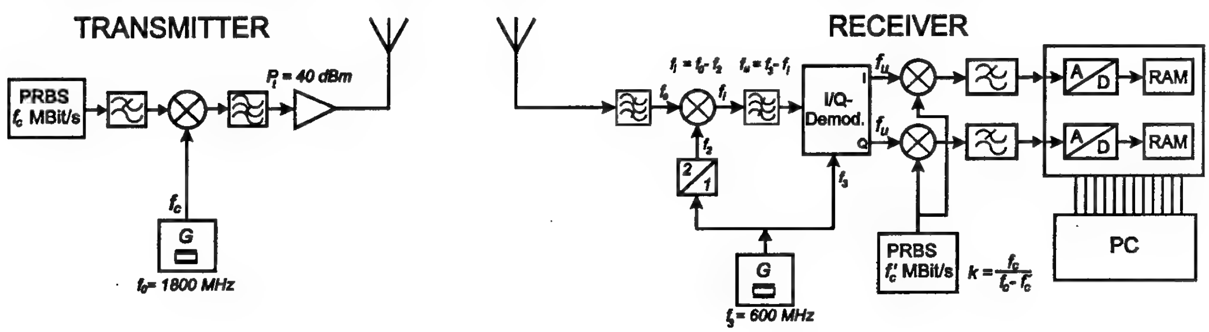

Figure 1 : Principle of the channel sounder

A carrier is modulated with a PRBS-signal and transmitted via a broadband monopole antenna. The receiver contains a two-step-demodulator with a I/Q-demodulation in the last step. Both channels (I and Q) are correlated with the same PRBS-sequence as used at the transmitter site, but at the receiver it is clocked with a frequency f_C' which is not identical with f_C. This leads to a beat, which allows a continuous correlation with a lowpass filter as described in [1].

The sequences are generated with ultra-fast ECL-circuits, providing very sharp slopes. The bitrate of 250 Mbits/s and the bandwidth of 200 MHz lead to a total resolution of the equipment of 5 ns. This time resolution corresponds to a difference in the path length of 6 cm. Due to this high resolution the channel sounder is very well suited for the determination of indoor channel impulse responses. The PRBS-sequence is limited to a period of 1023 bits. Combined with a clock of 250 Mbit/s this leads to a total length of the determined impulse response of 4.092 µs (or to path length differences of more than 1227 m). The period of the signal gained at the receiver output (due to the period of the PRBS) is very important, because it depends mainly on the difference between f_C and f_C'. The two clocks are temperature-compensated high quality crystal oscillators, but they have a very small drift in their frequencies. By sampling two periods of the output signal, the current value for $f_C - f_C'$ can be computed with the period of the output signal and so it is possible to calibrate the system with each impulse response measured.

As shown in figure 1 no connection between transmitter and receiver is necessary if only the magnitude of the channel impulse response is determined Further information about the phase (real and imaginary part of the impulse response) is not available, because the output signals are only shifted by 90 degrees and they are not in phase with the carrier signal.

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Indoor Radiowave Propagation : Channel Sounding and Parameter Extraction

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Efficient wireless indoor transmission represents a key technology to pave the way toward the realization of universal personal telecommunication (UPT). During the next decade a rapid development of new powerful indoor radio systems with capacities evolving from low to high data rates up to 155 Mbit/s can be expected. Correspondingly, a profound knowledge of the dispersive wireless broadband channel in the UHF, SHF and even EHF range is indispensable. On the one hand, global parameters like delay spread, coherence time and bandwidth, path loss, mean number of dominant paths etc. are needed to achieve a first approach to optimum system parameters. On the other hand, statistics of the random channel parameters have to be determined in order to simulate the system under worst case conditions before prototyping.

Consecutive measurements of the complex channel impulse responses (CIR) of the spatially distributed propagation paths permit the extraction of the corresponding wave parameters, e.g. complex amplitude, delay, number of dominant wave components or duration of local wave occurrence.

Wave propagation measurements are based on different principles. We describe a novel wideband channel sounder called *ECHO 24* (ETH Channel Sounder operating at 24 GHz) which makes use of optical microwave generation, achieves a 2 ns delay resolution and permits the determination of highly time-variant complex CIR by means of a correlation method. The latter procedure requires coherent demodulation, i.e. the transmitter and the receiver of the channel sounder separated by distances up to 50 m have to be synchronized properly. In the upper part of the SHF range and especially in the EHF range neither the use of atomic standards nor a connection with modern semirigid coaxial cables is possible because of frequency shift and attenuation problems, respectively. Moreover, the handling of stiff coaxial cables is rather cumbersome. Hence, a fiber optic antenna feeding concept has been developed which permits simple heterodyne detection and flexible low attenuation fiber links. Some measurements will be presented.

The channel sounder delivers a series of complex CIR evoked by the wave components impinging from different directions. The extraction of the data which is necessary tocalculate the corresponding wave parameters represents a fastidious task. Numerous algorithms are available which can be used to determine either a single parameter or at once a collection of them with satisfying precision. After presenting a survey of classic algorithms based on spectral and non-parametric estimation principles we shall introduce the SAGE (Space-Alternating Generalized Expectation Maximization) algorithm. SAGE is an iterative procedure using maximum likelihood estimation which can be successfully applied for the simultaneous extraction of several wave parameters. It will be shown that the calculated parameters are in good agreement with the geometrical interpretation of the expected wave propagation in an arbitrary chosen indoor environment.

Hot Spot Analysis Experiments in GSM Cells

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In contrast to the assumption of a spatial uniform distribution for the instantaneously active subscribers often required in model calculations, there exist so called *hot spots*, i.e. regions of increased activity in the uplink, within many cells of a mobile communication system. Generally it is of course important for network operators to know the location of such hot spots as accurately as possible, since they may use this information for network optimization. In this contribution a measuring method is discussed, which is based on *radio direction finding (RDF)*. Because RDF techniques are not applicable in mobile communication systems without the knowledge of the air interface, we concentrate our discussion to the GSM (global system for mobile communication) here. Nevertheless the considerations presented are applicable to every cellular radio system that uses FDD/TDMA (frequency division duplex/time division multiple access).

Hot spot analysis in a GSM cell may be performed in the following way: Two direction finder sites are chosen carefully within the cell. The usual geometric constraints concerning the locations of the direction finders in relation to the transmitter, of which bearings have to be taken, have to be considered. Especially a direction finder location at or close to a BTS seems to be useless, since electromagnetic influences have to be avoided. On a specific uplink frequency and in a specific timeslot the directions of arrival (DOAs) at the direction finders are measured and from these two azimuths the location of the mobile is determined and entered into a two-dimensional histogram, the cells of which form a grid over the GSM cell. The locations are measured for every timeslot and such two-dimensional histograms are taken successively for each frequency used in the cell. If all these histograms are superposed, the uplink activity within the cell may be displayed and hot spots can be detected. Of course the observations should be taken over longer time intervals (e.g. some hours or even a day) in order to obtain statistical sufficiency.

It is possible to use more than two direction finders within the cell. But in order to obtain reliable measurements, it is absolutely necessary to take the bearings of all direction finder sites exactly at the same time.

During the summer 1997 field tests dealing with direction finding and with hot spot analysis in GSM cells were carried out in two German cities. The results indicate that radio direction finding can successfully be applied to GSM signals. Especially multipath propagation seems to be insignificant to the determination of the angle of arrival for electromagnetic waves at 900 MHz, if a suitable direction finding algorithm is used.

The lecture deals with the following topics :

- Discussion of the direction finding and radio location algorithms as well as the components (antenna, receiver) used in the experiments.
- Realization of the experiments for hot spot analysis.
- Presentation of selected experimental results.
- Demonstration of the evaluation software.

Performance Evaluation of Smart Antenna Systems based on Deterministic Propagation

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In order to evaluate the performance of smart antenna systems for the use of SDMA in future mobile communications systems the algorithms for DOA or signal parameter estimation have to be imbedded in realistic environments. Therefore realistic models of time variant and frequency selective mobile radio channel including the antenna characteristics with inherent coupling effects are essential for characterisation of the total system. With increasing frequency a deterministic modeling of the channel becomes a dominant prerequisite.

Based on a 3D raytrace simulation tool including all effects of wave propagation mechanisms the directionality of the radio channel is weighted with the directivity of the antenna array including all polarization and coupling effects calculated by an antenna simulation tool. These simulations interact with a system simulation tool providing adequate modulation and coding features as well as analogue imperfections. Multipath and fading phenomena are taken into account: field strength prediction, angular and time delay spread evaluations could be derived for detailed investigations and comparisons between different environments, different or/and adaptive antenna characteristics (geometrical variations or beamforming algorithms) and special algorithms for DOA or signal parameter estimation. The complexity of the channel environment can be varied by the proper choice of the relevant parameters in dependence of the used frequeny and the topological structure. Simple scenarios give a closer impact of the sensitivity to modifications of parameters like material, dimensions of obstacles or antenna positions. More complex scenarios can be used to evaluate the improvement caused by the adaptivity of the antenna. The channel impulse responses are determined for all points of interest by their individual attenuation, direction and time delay for a given frequency and the position of the base station antenna. By the hierarchical structure of the simulation tools an efficient design and optimization process of smart antenna systems is possible under consideration of individual criteria of quality.

For reasons of flexibility the 3D raytrace program assumes an ideal antenna characteristic. The impact of the base station antenna can be added in two ways, dependent on link direction :

* In the uplink case the induced currents in the antenna are calculated and weighted by the time-variant signals, which impose the input data for the estimation algorithms.
* In the downlink case the radiation pattern for each polarization is calculated with all inherent coupling mechanisms and then convoluted with the channel impulse response.

The antenna characteristic of the mobiles can be simulated an equivalent way for purpose of diversity.

Capacity Improvement Using Smart Antennas

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A new classification of the gain obtainable by Smart Antennas is introduced: 'Spatial Filtering for Channel Improvement' (SFCI). It represents a further aspect of improved system capacity by means of Smart Antennas, i.e. the use of higher order modulation methods and higher bitrates.

With the aid of a simple channel model which takes spatial information into account, the maximum obtainable bitrate gain has been determined (figure 1). Given a certain scatterer geometry, it could be shown that the maximal signal path and the delay spread decrease if the antenna beamwidth is reduced. The maximum possible bitrate gain has been deduced from the delay spread in conjunction with the requirements for a frequency-nonselective channel. an enhancement of the bitrate is noticed when increasing the number of antenna elements which corresponds to a smaller beamwidth.

A high bitrate cannot be maintained at high mobility due to the changing channel characteristics and the speed of the adaptative tracking algorithm which is limited by the available processing power. So a user with high mobility is limited in the transmittable data rate, whereas an increased capacity can be utilized for users with limited mobility by means of Smart Antennas in order to provide higher data rates. Therefore, Smart Antennas will enable a trade-off between mobility and data rate (figure 2). This concept is investigated in the IBMS project (Integrated Broadband Mobile System), where three Network Service Classes (NSC A-C) have been introduced according to support different degrees of mobility.

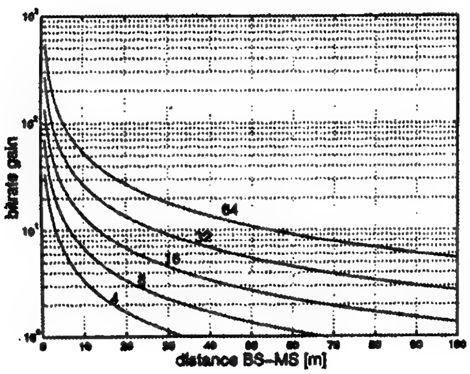

Figure 1: Maximal bitrate gain assuming a simple channel model with Smart Antennas

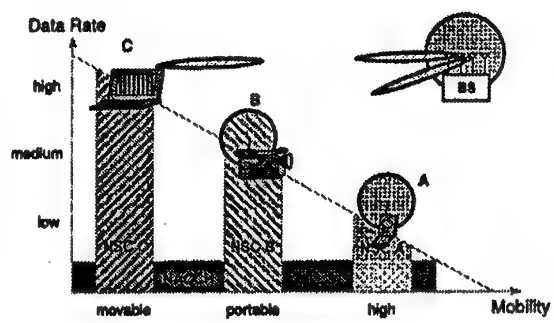

Figure 2: Trade-off Between data rate and mobility

For a simple capacity analysis the SIR has been determined for a certain number of users assuming a 7 cell cluster. The results indicate that NSCs A and B can serve the same number of users in the uplink, although the data rate in NSC B is much higher, while the absolute number of users per cell in NSC C is smaller due to stronger interferences caused by Smart Antennas at the mobile terminal. However, if the network capacity (defined as number of users per cell times bitrate-to-bandwidth ratio) is considered, NSC C proves to be most efficient due ton its data rate.

Some key features of the presented concept such as tracking of slowly moving users, switching between NSCs, and the use of higher order modulation methods shall be demonstrated in the course of the IBMS project by means of a hardware demonstrator. Our Smart Antenna testbed consists of an adaptative antenna array for 5.2 GHz with 8 vertically polarized single radiators spaced at $\lambda/2$ distance at the base station, while the mobile station is equipped with omnidirectional antennas. The feasibility of this concept has already been shown in MATLAB based simulations.

Session M05
Wednesday, July 15, PM 13:40-17:20
Room R03
Near Field 4 : RF/Microwave NF Techniques
Organisers : J. Ch. Bolomey, L. Jofre
Chair : L. Jofre

Transient and Frequency Domain Field Measurements with an Isotropic Photonic Sensor

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Montena emc

Since the beginning of the first attempts to develop high frequency field sensors, engineers where confronted with enormous difficulties to design miniature sensor heads incorporating modulators or rectifiers with sufficient sensitivity, dynamic range and electrical isolation. Most commercial field probes use simple rectifier diodes with intrinsic passive bias to produce a dc signal which is led to a metering unit either by highly resistive conducting lines or by a digital optical link. Besides having a limited sensitivity, a reduced dynamic range and a significant temperature drift, such probe systems with rectifier diodes do not transmit any information about phase or frequency. Other attempts to develop miniature broad band electronic modulators and optical links failed or the outcome was unpractical because of its dimensions and high energy consumption.

Our earlier developments of isotropic active probes for radiation hazard applications in the radio frequency bands (75 kHz to 110 MHz) used conventional electronics and the technique of the double loaded loops to measure simultaneously the electric and magnetic field with one hybrid probe head. The success of these probes have lead to further investigations for field measurements up to 1 GHz using fully passive electrooptic Lithium Niobate ($LiNbO_3$) modulators. These modulators fulfill the tight requirements for high frequency field sensors : they provide high integration, fully passive operation and very high bandwidths up to 40 GHz.

Our recent prototype development of a fully triaxial photonic field probe is capable to measure transient and continuous wave, electric and magnetic field. The miniature probe head incorporates nine electrooptic Lithium Niobate ($LiNbO_3$) modulators packaged in purely dielectric material. A remote low noise laser source feeds the nine electrooptic $LiNbO_3$ modulatores with connected sensor antennas. The laser light is guided by one polarization maintaining (PM) fiber to the sensor head. A PM splitter then divides the laser beam into 9 channels. The sensor antennas deliver their electrical signal directly to the modulators, where they are converted to nine intensity modulated laser beams (6 signals from 3 double loaded loops plus 3 signals from 3 dipoles). The light signals are finally converted to electrical signals again by 9 remote photo detectors.

The passive electrooptic modulators cover a frequency range from dc to 3.5 GHz and yield a dynamic range of morE the 120 dB. Further our measurements prove in the range dc to 1 GHz an amplitude ripple of less than ± 0.5 dB and a phase diviation within ± 5°. The modulator input capacitance has been minimised to provide maximum electric field sensitivity in conjunction with a broad band dipole antenna. The resistive loads of the double loaded loops where directly integrated on the surface of the electrooptic modulators.

The planned paper will not only give an insight to the functioning of the electric and magnetic field sensor but will also present first practical measurements in situ. There we intend to show diverse examples of frequency domain measurements (e.g. broadcasting transmitters, mobile phone and GSM base station) as well as fast transients pulse measurements with rise times in the subnanosecond range. These first results indicate clearly, that we developed not only a probe for radiation hazard and frequency domain measurements but also for almost all applications in modern transient field measurements techniques like high power microwaves HPM, pulse scattering, transient radar, EMP and ESD.

Antenna analyser using the modulated scattering technique

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This object of this paper is to present the principle of an antenna analyser using the modulated scattering technique and developped by the company ESTAR. This analyser covers a broad frequency band extending from 100 kHz to 15 GHz, with 5 sub-bands. It basically consists of a receiver and an optically modulated probe. The probe is a resonant circuit which is tuned at the operating frequency, the Q-factor of which is modulated at 5OO Hz by a photoresistor illuminated by an optical fiber. The receiver allows to perform vector measurements from a single side band analysis of the modulated RF test signal. The modulation of the RF signal is achieved either internally (modulation of the carrier) or externally (modulation of the probe), according to the selected operating mode. In the external mode, the modulation is directed toward the probe via an optical fiber.With the optically modulated probe, RF current distributions on antennas as well as near-field amplitude/phase measurements are equally possible. The internal mode is particularly devoted to testing transmitting equipment under use and for shielding efficiencies. The measurement process can be considered for both in-lab or in-situ applications. Different examples will be provided for illustrating the flexibility and the performances offered by such an antenna analyser.

Broadband and low interaction rapid cylindrical near-field facility

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This paper reports recent improvements of the rapid near-field facility developped at Supelec [1]. This facility, which is using a modulated probe array, has been especially designed for providing broad frequency band capabilities as well as low interaction between the antenna under test and the probing array. This modulated probe array consists of 128 dual polarized elements. The nominal frequency band extends from 1 GHz to 12 GHz, but can be also operated below or above with degraded performances. The main characteristic of the experimental setup is that the MST probe array and the associated auxiliary antennas are located on the focal lines of a cylindrical elliptical reflector. The probe array is used in a reflecting mode, a configuration which allows to achieve broad frequency band coverage at a minimal cost and complexity [2]. Furthermore, deporting the auxiliary antenna versus the test antenna ensures very low interaction, while focusing each of the probes on the auxiliary antenna, via the elliptical reflector, provides a good sensitivity. As compared to earlier papers, this one presents performance improvements resulting, mainly, from the design of a new auxiliary antenna and from an overall increase of the receiver performances in terms of sensitivity and stability. The new auxiliary antenna is constituted with an array of 48 spirals, the length of which, 2.35 m, is significatly larger than for previous pill-box or slotted waveguide configurations.

Results obtained with different test antennas illustrate the overall performances of the near-field facility. Both non-directive and directive antennas have been considered, such as portable GSM and DCS telephones, at 915 MHz and 1.8 GHz respectively, or reflector antennas with diameter up to 30 wavelengths. A particular attention has been paid for assessing, firstly, the troncation effect resulting from the finite height of the probe array, namely 2.35 m, for a probe array / test antenna distance ranging between 0.7 m and 2.7 m, then, the interaction level between the probe array and the antenna under test, and, finally, the impact of the probe dispersion compensation procedures. Compensation of the residual interaction effects are obtained by measuring the near-field distribution at different distances and by averaging the corresponding far-field patterns. Comparison to standard near-field measurements conducted with a single probe (open waveguide), mechanically translated, has allowed to quantify the far field pattern accuracy. For instance, 2 dB peak to peak deviations at -35 dB from the main lobe level are typical. Such an accuracy can be obtained, over one decade frequency range, at a measurement rate of 1,000 points per second. Such a measurement rate corresponds to an overall near-field measurement duration of the order of a few ten seconds, according to angular width on which the far-field has to be determined. The results obtained confirm that MST probe arrays constitute a convenient solution for both rapid and accurate near-field measurements.

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Recent Developments in Electromagnetic Diagnosis Using Near-Field Techniques

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Introduction

Past studies have been devoted to the location of ports of entry/leakage (POE) of complex objects which shapes were known. These ports of entry are retrieved from near-field measurements performed on a sphere surrounding the device under test (DUT). Until now, the object was assumed to be perfectly conducting with only small apertures and simple shapes of generic type. This paper presents recent extensions for dealing with true objects including large apertures and/or composite materials or coating. Preliminary assessments, including experimental validation, are presented.

Localization of entry/leakage ports

The localization of entry/leakage ports is achieved within a three steps procedure. The first one consists in measuring the near-field radiated by the object under test over a sphere surrounding it. Such measurements can be performed with the SOCRATE facility available at the Centre d'Etudes de Gramat. The second step aims at retrieving the current distribution existing on the object, the shape and the dimensions of which are assumed to be known. This three-dimensional linear and ill-posed inverse scattering problem, is solved *via* a Tickhonov-type regularization procedure associated to the generalized-cross-validation method to determine the regularization parameter. The reconstruction scheme requires the object be perfectly conducting. In the third and final step, the entry/leakage ports of the object are localized *via* the calculation of the tangential electric field distribution on the object. This electric field components are expected to vanish everywhere, except on the apertures from which the object radiates or receives external radiations. Practically, to avoid singularities, the electric field components are calculated on a surface "parallel" to the object, and distant from a small fraction of wavelength. A compromise is necessary to maintain a convenient discrimination between metallic parts and apertures, and to avoid numerical difficulties.

In this paper, the diagnosis capabilities are assessed on true near-field data obtained with the SOCRATE facility. Reconstructions are performed on realistic objects such as missile head exhibiting large apertures (seeker radar) and not perfectly conducting. Very reasonnable results are obtained, in spite of the fact that the initial infinite conductivity assumption is not fully verified. Further studies, to obtain additionnal information concerning the role of magnetic currents resulting either from large apertures or composite materials, are presented. A first way of investigation is to perform extensive numerical simulation with a Finite Differences in Time Domain (FDTD) code to determine the range of validity of the perfectly conducting reconstruction scheme in the case of composite materials. More particularly, for large areas in wavelength, the conductivity below which results are similar with those of a metal is determined. A second way is directed towards the possible use of magnetic currents for improving the reconstruction of the apertures.

Conclusion

This paper presents results from diagnosis of realistic objects and provides additional information for the extension to large apertures and composite materials. More prospectively, it also addresses possible improvement of the spatial resolution by taking into account the magnetic current distributions equivalent in the formalism.

Plane Wave Synthesis for Near-Field Bistatic RCS Measurements

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Several methods have been previously proposed to solve the Near-Field (NF) scattering measurement problem [1]. Most of them allow to reconstruct Far-Field (FF) scattering patterns by performing a numerical double deconvolution of coupling integrals after NF data collecting. These data are obtained through a double scanning, of transmitting and receiving NF surfaces. SO, considering full size 3D targets indoor measurements and classical mechanical scanning, the extremely high number of samples required by these global NF methods leads to prohibitive time measurement duration.

Meantime, the development of advanced electronically-scanned modulated scattering arrays [2], designed for rapid and efficient NF measurements, particularly NF scattering measurements, gave a new rise to studies related to the NF RCS measurement problem and great hopes to solve it practically.

Whereas most of previous methods consider this problem as a global NF problem, we propose a new approach by separating it in two distinct NF problems :

- As a first step, we have already demonstrated that the measurement of the near fields scattered by a target under Plane Wave (PW) illumination could be considered as a classical NF antenna measurement. In this configuration the FF RCS pattern can be retrieved using classical NF/FF Transform algorithms [3].
- This paper presents the second step of our approach, that could be resumed by : how can we create a sufficient PW at short distance from the transmitting antenna, much shorter than the classical μFF distance required between the transmitting antenna and the target ? If such a NF Plane Wave Synthesis (PWS) is achieved, the problem is simplified and equivalent to the first step.

The NF PWS is obtained here by using spectral transformations applied to arrays of radiating elements [4]. This method is flexible and allows to adjust parameters such as number of sources and step between two elements. For a given Plane Wave Zone (PWZ) extent, it is quite simple to optimize the PWS trough a compromise between the number of sources and the array/target distance.

We present results of optimized NF PWS applied to bistatic RCS measurements in two cases :

- 2D PWZ, using infinite line sources as transmitting array elements; this case is well-suited to targets offering one dimension much longer than the others; it is illustrated by the formulation of the diffraction and the plot of the bistatic Scattering Width (SW) pattern of an infinite axial cylinder located at the center of the 2D PWZ.
- 3D PWZ, using finite dipole sources; this more general case for any 3D target is illustrated by the formulation of the diffraction and the plot of the bistatic RCS pattern of a sphere located at the center of the 3D PWZ.

In both cases, patterns retrieved are compared to those theoretically obtained for targets illuminated bt true PW and the influence of PWS parameters is studied.

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Derivation of the Far-Field Target R.C.S from Near-Field Measurements

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The development of new equipments (planes, ships, satellites, ...) often requires the radar cross section (RCS) of these objects have to be well known under far-field condition in which electromagnetic waves are assumed to be planar. Nevertheless, the dimension of some measured objects may be too large to carry out the far-field radar cross section. Assuming the distance between the measured object and the probe antenna must be higher than $2D^2/l$, with D the largest dimension of the object and l the wavelenght, the required surface of measurement for high frequency condition is then very large. Furthermore, if RCS measurements are made under outdoor condition, perturbations generated by the weather and the vegetation must be taken in account and it requires high performance equipment. These facts create heavy constraints particularly in a financial point of view. In order to solve these problems, the RCS is measured under near-field condition in the compact space of an anechoic chamber using near-field scanning techniques developped for antenna measurements and extended to radar application. Then, far-field RCS can be estimated by computation on near-field RCS measurements.

Under near-field condition, an object is irradiated by a nearby source emitting spherical waves. Each element of the object scatters elemental spherical waves which propagate to the probe location where they are received uniformly. In far-field RCS measurements the object is irradiated by an uniform plane wave from the source antenna and only the singular plane-wave component of the field which is scattered by the object in the direction of the receiver is accepted. To compute an estimation of the far field, we must transform near-field transmitted and scattered spherical waves into far-field incident and scattered planes waves. In this purpose, we have defined a theoretical method to compute far-field radar cross section from monostatic spherical near-field measurements, using a transformation called "*spherical correction*" and based on a physical optic approach.

For a monostatic spherical geometrical configuration, the studied target is located at the centre of a virtual measurement sphere *(S)* which radius R is constant and near-field RCS is measured for several positions $M(\vec{n})$ of the probe antenna over the surface of the sphere *(S)*. Assuming that object is locally irradiated by uniform plane waves, the observed scattered near field over the spherical surface *(S)* enclosing the target can be used to compute an estimation of the scattered field at any location outside this enclosing surface by simply propagating the observed near field using Huygens principle. The far field in a vectorial direction $\vec{u}$ can be derived from Stratton-Chu relations though the following expression called "*Huygens two-dimensional integral in monostatic case*" :

$$E_{ff} \approx K.\int\int_{(S)} E_{meas}(\vec{n})\exp\left\{\frac{j2\pi f}{\lambda}R(1-(\vec{n}\cdot\vec{u}))\right\}dS$$

Applications of a-MST Probe Arrays to Rapid Diagnostic of Anechoic Chambers and Compact Ranges

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This paper describes applications of probe arrays based on the Advanced Modulated Scattering Technique (A-MST) to accomplish rapid diagnostic imaging of anechoic chambers and compact ranges.

The technical feasibility of performing fast diagnostic testing of large anechoic chambers by using A-MST probe arrays in conjunction with the MUSIC imaging algorithm was demonstrated based on the outcome of experiments conducted at the compact range/anechoic chamber facility at the Centre National d'Etudes Spatiales (CNES) in Toulouse, France, under the sponsorship of the U.S. Air Force. In particular, a wideband (1.5 GHz - 6.0 GHz) linear array of 64 dual-polarized modulated scattering probes (cf figure 1) was installed on the 7 - axis positioner located of each of the 64 probes along the 5.7 foot length of the array was measured in less than 10 milliseconds. A special version of the MUSIC code was developed and utilized to obtain high resolution images of the chamber. (cf. figure 2).

Two pre-processing techniques are applied. the first one allows to reduce the influence of the beam incoming from the reflector by operating an average in two-planes separated by half of the wavelength. The decorrelation between the incoming plane waves is achieved by applying the second pre-processing. Those pre-processing algorithms are time consuming with a classical single probe measurement system because they require the acquisition of a large amount of data. In this context, the use of the A-MST probe array system permits to reduce drastically the measurement time.

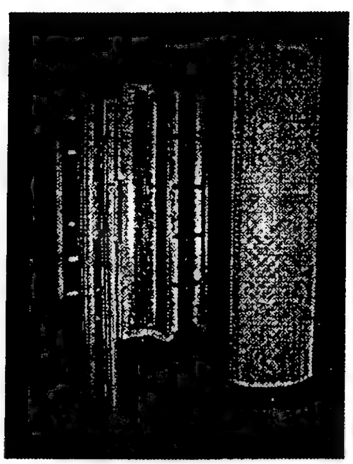

Figure 1: *View of the A-MST probe array in SATIMO's NF measurement Facility*

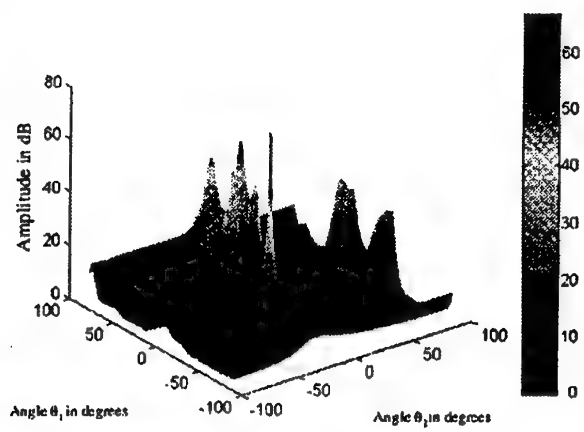

Figure 2: *3-D perspective plot of the 2-D MUSIC Spectrum for the CNES CHAMBER*

Matrix Formulation for Antenna Diagnosis and Near-Field to Far-Field Transformation

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Classical methods used in near filed (NF) to far field (FF) transformation have focused their attention in the optimal representation of the near filed samples with a series of coefficients (modal expansions). In order to recover all the coefficients without errors the near field has to be measured over the whole surface, and for simplicity, the surface must be canonical (ie. plane, cilinder, sphere).

A matrix method formulation is presented. The method models the antenna with a planar surface (plane aperture) that covers physically the antenna under test and locates equivalent magnetic currents (EMC) over this surface. Near field data is used to determine these magnetic currents acording a matrix formulation, solving a linear set of equations. Far field is then obtained from the EMC. The information about the finite measurement surface and antenna geometry is used, so results are better than in classical spectral formulation (SF). Also, while SF requires data to be taken in a canonical surface, EM is more flexible enabling data to be taken in an arbitarry surface .

The method can be applied also to the antenna diagnosis. In that case the matrix formulation relates the currents over the antenna with the near field samples. The advantage in front of classical formulations is that the antena can have any geometry. The method is very useful, specially for array antennas, where the element excitations are recovered. We will present results of the method from real measurements, both for near field to far field transformation and for array diagnosis.

35m x 16m Large Nearfield Measurement System

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One major problem in the development and manufacture of sophisticated antennas is the measurement of the antenna performance. The techniques used in the past are becoming less capable of determining the performance of advanced antennas due to various problems such as weather effects, multipath, antenna gravitational distortions and security. In the 80s the antenna measurement techniques have evolved from a scientist's tool into a science itself. The developments followed the introduction of the computer that almost all pattern test ranges are now equipped with some computational equipment. Nearfield measurement technique is one of the most powerful tools for a fast and accurate method of determining the antenna gain, pattern, polarization purity, beam pointing and other parameters of interest to an antenna engineer [1]. The planar nearfield technique is an effective method for measuring the performance of large, high-frequency spacecraft antennas and other advanced low sidelobe antennas [2].

In this project, we designed a planar nearfield measurement system, which is the largest scanner in the world, to accommodate the requirements of minimum 30m x 16m scan plane at the frequency range of 1-50GHz. The system hardware consists of robotic scanner, optics correction, and RF and computer subsystems. The scanner and part of RF equipment have been installed in an anechoic chamber of dimensions 40m L x 24m W x 25m H. The system provides X, Y, Z and polarization axes for probe positioning and includes and optical measurement package for precise determination of linear distance and positioning error. These measured errors are used to correct the probe position while scanning. With laser feedback the positioning error are 50 μm rms or less both the X and Y axes. Using the NSI structure monitor capability, planarity of the scan plane is correctable to within 50 μm rms. Computer system and Data Acquisition controller (DAC) is capable of cross-axis correction to improve overall scanner accuracy and planarity during the antenna measurement acquisition process. The environmental conditions during scan are 25 ± 3°C nominal temperature and 50 ± 10% relative humidity ranges inside the chamber.

For completing nearfield antenna range verification sources of errors are determined according to 18 term NIST error budget [3].

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Realisation of a Didactic Radar

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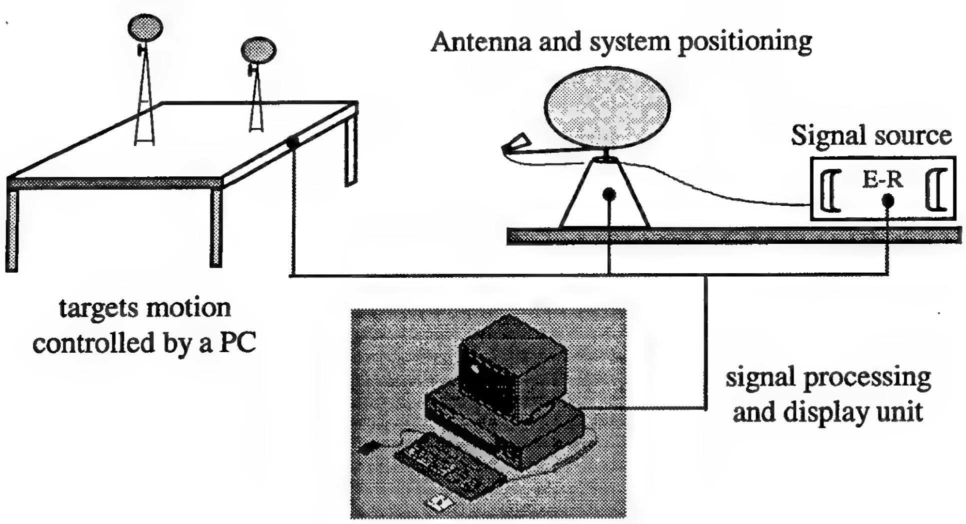
Introduction

The didactic radar has been designed to reproduce the main fonctions of a radar, combining hardware and software parts. Its particularities are the compactness, the azimutal and distance resolution to be used in a practical room, the multiple signal processings made by a computer, giving it a large evolutivity for the last and future radar processings. An interesting feature is the real time processing of the video signal on a computer.

Realisation

The radar is based on a continuous wave generation in X-band : the compression technique of 1 GHz band enables to simulate a 1 ns pulse, and to obtain a distance resolution of 15 cm. To achieve this, some precautions have been taken to obtain an excellent linearity of the frequency sweep, maintaining a small sweep time up to 15 ms. The didactic radar includes a positioning system for targets trajectories, a parabolic reflector associated with a horn, a emitter/receiver in X-band.



Signal Processings

Among the available processings, we can mention the localisation of the target, both in azimutal plane thanks to a directive antenna, and in distance axis with a pulse compression technique; the target is displayed on a PPI and scope A interface. It is also able to measure target velocity, and to estimate the retrodiffused power. With the addition of simulated clutter, we can calculate the detection and false alarm probabilities, such as a real radar. The mobile targets can be extracted from stationary clutter or other fixed targets thanks to VCM processings.

Session A08
Thursday, July 16, AM 08:40-12:00
Room 300
Coherent Effects in Random Media I

Organiser : V. Freilikher
Chairs : V. Freilikher, H. Ogura

Mie Scattering in a Magnetic Field

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We have performed perturbational calculations of light scattering from a dielectric "Mie" sphere exposed to an external magnetic field [1]. The small parameter is VBa, i.e. the Faraday rotation angle that applies to a direct passage of the light in the sphere.

The magneto-cross-section linear in the magnetic field is shown to exhibit a net "Hall" effect, i.e an asymmetry exists of the magneto-cross-section along the $\mathbf{k} \times \mathbf{B}$ axis for an incident wave vector $\mathbf{k}$.

These calculations have been carried out in order to obtain a better quantitative understanding of the genuine "Photon Hall Effect" [2,3] and the "Photon Magneto-Resistance" [4], both multiple-scattering phenomena and both verified experimentally by us. We shall discuss the implementation of our magneto "Mie solution" for one scatterer into a multiple scattering theory.

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Time Dependance of the Speckle in the Multiple Scattering of Waves in Random Systems

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In multiple scattering regime, information on the propagation direction or wave vector are lost and geometrical optics laws cannot be used for analysing images in turbid media. When the scatterers are moving, it is well known that a quasi-elastic scattering occurs in the single scattering regime. In multiple scattering regime, the time correlation of the intensities $<I(0)I(t)>$ reflects the motion of the scatterers at very short time scale, typically the time elapsed for a displacement of the scatterer on the wave length divided by the number of scaterings in the characteristic path of diffusion. Since 10 years important progress have been done in this field - brownian motion of suspensions of colloids, foams, liquid crystals, laminar and turbulent flows - and today, the principles of this method can be used for imaging the flow of loaded fluids in complex and turbid media. More elaborated correlation functions in time - so called C2 and C3 correlation function - would be discussed in recent experiments.

Numerical Study of Band Gaps Generated by Randomly Perturbed Metallic Photonic Crystals

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Metallic photonic crystals have recently attracted significant interest in the microwaves region where they could be used as efficient microwaves reflectors or microwaves cavities. It is now well known that the most dominant feature of these structures is a large forbidden band gap extending from zero to a cut-off frequency. This property may be interpreted as a consequence of the following result: a metallic photonic crystal can simulate a material having a plasmon frequency in the microwaves region. This fundamental result has been obtained by J.B. Pendry for a 3D simple cubic lattice and for low frequencies [1], and mathematically demonstrated by D. Felbacq and G. Bouchitté for a 2D square lattice (set of infinite perfectly conducting parallel rods with square elementary cell), using a limit analysis technique [1].

As suggested by Sievenpiper et al. [3], the existence of such a band gap could not be linked to the periodicity of the structure (in contrast with what happens for dielectric photonic crystals) but only to its metallicity. In order to demonstrate this conjecture in the case of 2D metallic photonic crystals, we have performed a rigorous electromagnetic calculation of the gaps generated by a periodic metallic photonic crystal with a square lattice, then by photonic crystals obtained by translating each rod in a random manner inside the elementary cell.

It will be shown that this strong perturbation of the positions of the rods do not generate an important change in the upper limit of the gap. Below this cut-off frequency, perturbed and unperturbed crystals behave actually as effective media with frequency dependent negative dielectric constant.

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Static Phase and Dynamics of Microwaves in Random Media

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The study of intensity statistics of waves propagating in random media has revealed strong fluctuations and long range correlations which are examples of the underlying wave nature of the field [1]. Statistics of the complete field itself (amplitude and phase) rather than the intensity would allow to go further in this study. For instance, field-field correlation measurements give a simple way to separate between short and long range intensity correlation. The microwave domain where phase is measurable is a paradigm to explore the statistics of the field in random media. Recently [2], we presented a statistical study of the cumulative phase of microwave radiations transmitted through a random arrangement of polystyrene spheres. In such a disordered system, the wave is multiply scattered and the field measured at the detector is a complex sum of the field of all the partial waves scattered in the medium interfering at the detector. Even though the number of possible paths followed by the partial waves is large, the total phase at the output does not self average but exhibits large fluctuations.

We show in the present paper that the phase can be simply related to the dynamics of wave transport in random systems in terms of the dwell time of the photons traversing the medium. This reveals in turn strong connections between the static phase and the time domain properties of the medium and unveils at the same time unexpected strong fluctuations of this dwell time. We found that, in the limit of very long pulse, the delay time is equal to the phase derivative. Phase singularities in the speckle pattern at the output of the sample is however responsible for the discrepancy between phase variations and dwell time for finite pulses. Contribution of these phase singularities is eliminated either by averaging over sample configurations or by weighing the phase derivative by the number of photons at each frequency which gives an exact relationship between the dwell time for a finite pulse and the phase derivative of the static field. These connections open a new way of investigating statistical properties of wave dynamics in random media via the static measurements of the phase.

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Statistics of Microwave Radiation near the Localization Threshold

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We report the dramatic enhancement of intensity fluctuations as the localization threshold is approached. Three approaches are employed to bring a sample to the mobility edge: (1) The length of quasi-one dimensional random samples of weakly scattering polystyrene spheres contained in a copper tube is increased, (2) the scattering strength of three-dimensionally random collections of alumina spheres, with index of refraction $n = 3.13$, is maximized by varying the density and tuning the frequency through the region of the first Mie resonance, and (3) randomly positioned aluminum spheres are introduced within a cubic metal-wire network and the frequency is tuned through the band edge.

The polystyrene sample is contained in a 5-cm diameter copper tube with lengths up to $L = 5$ m. This is slightly greater than the localization length $\hat{\imath} = Nl/L$, where N is the number of transverse modes of the waveguide and l is the transport mean free path. Fluctuations of intensity as large as 50 times the ensemble average are observed for lengths $L = \hat{\imath}$ and the variance of the distribution of normalized intensity then equals 2.18 as compared to a value of unity in the diffusive regime. Our measurements demonstrate that the relationship between moments of the intensity and total transmission distributions, derived by Kogan and Kaveh for diffusing waves, holds up to the longest samples for which both the total transmission and intensity distributions were measured of $L = 2$m. For these samples the distributions in the absence of absorption were also found. The field spectra were Fourier transformed into the time domain. The field spectra in time were then multiplied by a factor $\exp(t/2\hat{o}_a)$, where $1/\hat{o}_a$ is the absoption rate, before being transformed back to the frequency domain. In this way, the influence of absorption can be removed even in strongly absorbing samples. For $L < \hat{\imath}$, the intensity distribution is only slightly modified by the presence of absorption.

In samples of alumina spheres and in the nearly periodic structures, the variance of the intensity, which gives the degree of nonlocal intensity correlation, is measured as a function of frequency and scatterer density. The strongest correlation is observed for volume filling fractions between 0.15 and 0.30 in the random alumina sphere samples and at filling fractions of 0.10 for aluminum spheres. The intensity distributions for these samples for equivalent values of the dimensionless conductance are compared.

Coexistence of Ballistic Transport, Diffusion, and Localization in Surface Disordered Waveguides

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The statistical properties of the transmission through a disordered waveguide constitute a long-standing problem which has attracted much attention in recent years from both theoretical and experimental standpoints. In this presentation we show that surface disorder, in contrast to volume fluctuations, produces enormous differences in the waveguide transmission properties of different guided modes. Naive considerations would suggest that if we introduced a localization length (which obviously must be much larger than that for the bulk scattering), we should just rescale the well known results leaving the rest unchanged. However, this is not the case: interference effects display themselves earlier than the complete mixing happens. Some modes become localized quite before the inter-mode coupling involves the other modes into diffusion. To analyze the problem analytically we derive the invariant embedding equations for the matrices of reflection and transmission amplitudes. For numerical simulations we choose the simplest geometry: two parallel planes with 1D deviation at one plane only. The results clearly reveal drastic differences in the behavior of the reflection and transmission amplitudes for each incoming mode and demonstrate the coexistence of quasi-ballistic, diffusive, and localized transport for different incoming channels within the same region of surface disordered waveguide. This phenomenon manifests itself through both the different behaviors of the one-channel-in/one-channel-out transmissions (average and fluctuations), and the anomalous crossover in the conductance from quasi-ballistic to localized regimes without a diffusive phase in between. Therefore, a waveguide with a random rough surface gives an example when the symmetry between channels is broken and we can observe all three regimes coexisting at the same system size. This phenomenon can be revealed experimentally by measuring either the transmission intensities of guided microwaves or light (or any other accessible electromagnetic or classical wave), or the anomalous conductance crossover in the electronic problem.

Disordered Microwave Cavities as a Model for Spectral Correlations in the Transition from Diffusive to Ballistic Regimes

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Inspired by recent works concerning the quantum transport in mesoscopic electronic structures [1], we suggest that random matrix theory should be relevant to describe the fluctuations of the transmitted field in disordered microwave cavities even when accounting for the losses which are unavoidable at room temperature and which lead to moderate or strong modal overlap. In particular, we show that a specific model for a cavity with randomly positioned scatterers is adequate to analyze the long range frequency correlations that we exhibit in a 2-dimensional disordered microwave cavity. In this cavity, we use a vectorial network analyzer to perform measurements of the transmitted field (both amplitude and phase) over a large range of frequencies (ranging from 50 MHz to 20 GHz). These experiments allows us to study the cross-over from a *low frequency* regime where resonances are isolated to a *high frequency* regime where modal overlap cannot be neglected. Following a semi-classical approach devised in the field of *quantum chaos*, we present a theory for the spectral correlations which can account for both aspects of wave propagation in this kind of cavity, namely the ballistic and the diffusive regimes. This theory extends the range of validity of standard random matrix theory and is proposed as a simple alternative to the diagrammatic approach. This works is a natural extension of our previous findings concerning the validity of random matrix theory in a chaotic lossy cavity (a Sinaï shaped billiard) where we could illustrate the relevance of spectral rigidity predicted by Wigner-Dyson's Gaussian Orthogonal Ensemble [2].

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Scaling Properties in Highly Anisotropic Systems

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Scaling of the conductances and the finite-size localization lengths is generalized to anisotropic systems and tested in two dimensional (2d) and 3d systems. Scaling functions of isotropic systems are recovered once the dimension of the system in each direction is chosen to be proportional to the localization length [1]. It is also shown that the geometric mean of the localization length is a function of the geometric mean of the conductivities. The ratio of the localization lengths is proportional to the square root of the ratio of the conductivities, which in turn is proportional to the anisotropy strength t, in the weak scattering limit. We also investigate the localization behavior of weakly coupled panes and weakly coupled chains. It is found that the mobility edge is independent of the propagating direction [2], [3]. However both the correlation length in the extended side of the transition and the localization length in the localized side of the transition, differ substantially in the two propagating directions. We discuss, how this can possible explain the transport properties of high temperature superconductors.

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Can a Thermal Source Be Spatially Coherent ?

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Thermal emission of opaque surfaces is often regarded as a fundamentally incoherent phenomenon. Indeed, the thermally emitted field close to the surface of a body in local thermal equilibrium is often considered to be d-correlated. This yields the well-known sin(kr)/r shape for the cross-spectral density $W(\mathbf{r}_1, \mathbf{r}_2, w)$ (i.e., the time-domain Fourier transform of the electric field correlation function) of blakbody radiation[1].

Nevertheless, it has been shown that the *polarized* thermal emissivity of lamellar gratings supporting *a surface wave* (either a surface-plasmon or a surface-phonon polariton) displays peaks in particular directions, and at particular frequencies[2,3]. This is the signature of a partial coherence in the thermally emitted field.

In this study, we focus on *the spatial coherence* of the emission, i.e., on the existence of peaks in the emitted polarized monochromatic radiation, in particular directions. The physical origin of these peaks lies in the existence of the surface wave, which induces a spatial correlation of the near field along the interface, as qualitatively explained in ref.3. We present an analytical calculation of the cross-spectral tensor $W_{jk}(\mathbf{r}_1, \mathbf{r}_2, w)$ of the vector field along the interface[4], using a semi-classical approach based on the fluctuation-dissipation theorem[5]. The result shows explicitely the influence of the surface wave on the *p*-polarized cross-spectral tensor, which induces a long-range correlation of the field on the surface. This near-field correlation is responsible for the partial spatial coherence of the thermal emission.

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Session B06
Thursday, July 16, AM 8:40-12:00
Room G/H
Shape reconstruction and Object Identification

Organisers : Ch. Pichot, S. Caorsi
Chairs : M. Fiddy, A.G. Tijhuis

Target Identification from Limited Backscatter Field Measurements

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In many important applications it is frequently the case that only very few data points are collected from the illuminated target. The limited number of returns that might be received from a moving target under radar surveillance, or the limited angle backscatter data measured when attempting to image a buried target, are two examples.

In an accompanying paper the difficulties in imaging a strongly scattering and penetrable target are addressed. Even with the availabililty of complete sets of noise-free data, calculating a quantitative and high fidelity image of a target is a challenging problem. Here we specifically address the situation when there might be so little data that even in the weakly scattering case, i.e. when the first Born approximation can be assumed to be valid, one can not obtain a meaningful image. Under these circumstances there is little that can be done if there is no a priori knowledge about the target under investigation.

Let us assume that the actual target is a member of a limited class of possible target structures. This permits the use of a spectral estimation method which we refer to as the PDFT method. When the PDFT is implemented in an adaptive fashion, a cost function that determines the closeness of fit of various target possibilities to the limited measurement data can be monitored. We have applied this approach to very limited but real measured data from an essentially first Born scattering structure, namely a model of a missile.

We have shown that one can systematically shrink a perimeter function in the image space, this being our a priori information about the likely target shape, and monitor the energy of the PDFT estimate, to determine the "best" fit shape function. The perimeter or shape function leading to the minimum energy PDFT estimate proves to be an excellent indicator of what the original target silhouette was like. We have studied how the optimal perimeter function can be efficiently determined in simple steps by shrinking and growing the size of the shape function in a systematic way [1].

In this paper we will describe a more direct approach which allows rapid target identification as data are being collected. We also have considered the use of this approach for the case when several possible target shapes are expected. The extension of this method to the case of strongly scattering targets will also be examined.

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A Microwave Holographic Imaging Technique based on the Method of Auxiliary Sources

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The reconstruction and the analytical continuation of wave fields have been studied by many researchers [1], while the fundamental principles and the mathematical formulation of the Method of Auxiliary Sources (MAS) is given in [2,3]. The present holographic method of wave field reconstruction is based on the MAS, requiring also that the scattered field is known at a certain distance from the scatterer. Conventional MAS is based on the representation of the scattered field by a superposition of the fundamental solutions of the corresponding wave equation, denoted as auxiliary sources distributed on an auxiliary surface which is selected to be always inside of the non physical area of the scatterer. Then, the scattered field (i.e. the weighting coefficients of the auxiliary sources) is determined by forcing the fulfillment of the proper boundary conditions. A new idea of using the MAS in inverse scattering problems is introduced in the present paper, by selecting auxiliary sources which generate fields propagating towards them, i.e. the phase velocity of the fields should show waves approaching the sources rather than outgoing.

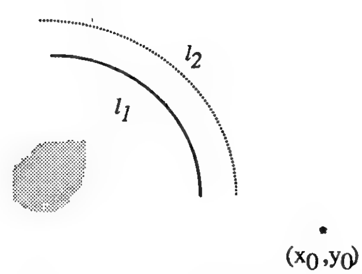

Fig. 1 **: Holographic Imaging Technique**

To this end, we consider a scatterer (Fig. 1), illuminated by an incident field induced by a source placed at (x_0, y_0) and we assume that, on a certain surface at some distance from the object, the scattered field (amplitude and phase) is known/measured. The aim is to reconstruct the scattered field around the scatterer up to its singularities (sources of scattered fields or re-emitters). For this purpose, auxiliary sources are distributed on a surface l_2, near the one used to measure the field's data. It is of great importance to determine the type of functions to be used at the auxiliary sources distribution. Since the auxiliary sources will be employed to describe a field propagating towards them, the phase velocity of the scattered field should be pointing towards the sources. Thus, it is necessary to use appropriate sources, which will behave as absorbers. The measured scattered field is then matched to the field created by the auxiliary sources. The latter determines the amplitudes and phases of the auxiliary sources, by solving the corresponding system of linear equations. Due to the uniqueness of the analytical continuation of the wave field, the field created by the auxiliary sources will restore the field up to the main singularities into the non-physical area of the scattered field of the object. The validity of the proper boundary conditions (e.g. short circuiting of the total electric field) can be then used to indicate the shape of the scatterer.

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Determination of the Orientation of the Cylindrical Bodies by the Use of Scattering Data

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The main objective in inverse scattering problems is to recover the geometrical(location and shape) and physical(constitutive parameters) properties of inaccessible bodies by examining its respond to a given excitation(electromagnetics , acoustic, elastic etc). During the last two decades many efforts have been devoted to the investigation of such problems arising in various fields of physical and engineering sciences. Among the most well studied targets are cylindrical bodies with *known orientations.* Knowledge of orientation from the beginning plays a crucial role in the investigation of these problems because it makes it possible to reduce them into *two-dimensional scalar* problems. However for realistic/practical problems, the orientation of the cylindrical body is also unknown. This is especially important in problems connected with bodies buried in a half-space or slab. In those cases, by choosing the coordinate system properly, one can reduce the problem to one that involves scalar field components and is two-dimensional. If the orientation is not known, then it is necessary to consider 3D implementations of the vector fields.

The aim of this paper is to determine the orientation of the cylindrical bodies from collected scattering data. Once the orientation is obtained, the other properties can be recovered using known methods. The method given in the present work follows the Born approximation.

Reconstruction of Inhomogeneous Media from Real Electromagnetic Scattering Data

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The so-called IPSWICH electromagnetic scattering data are studied. These data are experimental data relative to time-harmonic electromagnetic scattering of cylindrically symmetric objects. We propose a mathematical model that reduces the solution of the problem of the reconstruction of the shape of the objects considered to a nonlinear integral equation.

Two numerical methods to solve this nonlinear integral equation are proposed. The first one is a linearization followed by a multigrid technique to solve the resulting linear problem. The linear integral equation is ill posed, so that we use "a posteriori" information obtained on a coarse grid from the experimental data as "a priori" information on a fine grid in order to stabilize the problem. The second one solves the full nonlinear integral equation introducing one auxiliary variable. In particular we try to split the experimental data in two parts; the part coming from the conductors present in the scene and the part coming from the penetrable obstacles. This is done in order to reconstruct the conductors in the first few iterations and later the penetrable obstacles.

These methods are able to reconstruct simple shapes such as circles, triangles,... both in the case of penetrable obstacles and conducting obstacles.

Successive Approximations, Propagation Algorithms and the Inverse Obstacle Problem

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Approximate backpropagation (ABP) methods have been used to identify the shape of axially symmetric acoustic scatterers in the resonance region from full aperture data [C1]. More recently one such method has been applied to the electromagnetic case [C2], where the Ipswich data [MK1] are available. ABP methods have relied on a heuristic relation between the expansion coefficients, which represent the scattered wave in the far zone and, respectively, on the obstacle boundary, Γ, and have led to minimization algorithms.

In spite of satisfactory computational results, the well - posedness of ABP remains an open problem. A pertaining result, which may justify the method, is the following.

Let λ, μ be multiindices, $\{\nu\mu\}$ be e.g., the family of outgoing cylindrical ($n = 2$) wave functions and $\{f\mu\} := \mathbf{f}$ be the sequence of far field scattering coefficients. Denote outward differentiation on Γ by ∂_N. Assume both series $\Sigma_\mu f_\mu \nu_\mu$ and $\Sigma_\mu f_\mu \partial_N \nu_\mu$ converge uniformly on Γ. Let $\mathbf{b}$ be a sequence of inner products in $L^2(\Gamma)$, which depend on the incident wave, u, and consider the operator $\Re\mathbf{L} := -\frac{i}{4}\left[\left\langle u_\lambda \middle|_\Gamma \partial_N \nu_\mu \right\rangle\right]$, where $u_\lambda := \mathrm{Re}[\nu_\lambda]$. Also, let L be the approximation order and Λ (L) the corresponding set of indices. Denote e.g., by $\mathbf{b}^{(L)}$ the finite sequence derived from $\mathbf{b}$ and by $\mathbf{c}^{(L)}$ the vector of least squares boundary coefficients, which solve $\left\| u + \Sigma_{\lambda \in \Lambda(L)} c_\lambda^{(L)} n_\lambda \right\|^2_{L^2(\Gamma)} = \min$.

Theorem. Assume $\mathbf{f}$, $\mathbf{b} \in \ell_2$ and $\Re\mathbf{L}: \ell_2 \to \ell_2$ is bounded. Let the spectral radius $r_\sigma[\Re\mathbf{L}]$ of $\Re\mathbf{L}$ satisfy $r_\sigma[\Re\mathbf{L}] < 1$. Then

a) $\forall\, \mathrm{b} \in \ell_2$, there exists a unique fixed point, $\mathbf{f}$, for the map $\mathbf{p}[t+1] = \mathbf{b} + \Re\mathbf{L}\mathbf{p}[t]$, $t = 0, 1, 2, \ldots$, obtained by successive approximations, started with an arbitrary $\mathbf{p}[0] \in \ell_2$;

b) let $\bar{\mathbf{c}}^{(L)}$ be the fixed point of $\mathbf{p}^{(L)}[t+1] = \mathbf{b}^{(L)} + \Re\mathbf{L}^{(L)}\mathbf{p}^{(L)}[t]$ with $\mathbf{p}^{(L)}[0] = \mathbf{c}^{(L)}$ and $\mathbf{p}^{(L)}[1] \equiv \mathbf{p}^{(L)}$; if $\left| f_\lambda - \bar{c}_\lambda^{(L)} \right| < \epsilon_1 \left| \bar{c}_1^{(L)} \right|$ and $\left| c_\lambda^{(L)} - \bar{c}_\lambda^{(L)} \right| - \left| p_\lambda^{(L)} - \bar{c}_\lambda^{(L)} \right| > 2\epsilon_1 \left| \bar{c}_\lambda^{(L)} \right|$, $\forall\lambda \in \in \Lambda(L)$, then forward propagation is effective i.e., $\left| f_\lambda - p_\lambda^{(L)} \right| < \left| f_\lambda - c_\lambda^{(L)} \right|$, $\forall\lambda \in \Lambda(L)$.

These results will be applied to a class of numerical problems and their practical repercussions on shape identification will be discussed.

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Convergence Rates of a Regularized Newton method for Inverse Scattering Problems

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The problem we consider is to recover the shape of a perfect conductor from measurements of the far field pattern of the scattered wave corresponding to one incident time harmonic plane wave in the resonance region. This problem is difficult to solve, since it is nonlinear and severely ill-posed. It can be formulated as an operator equation $F(q) = u_\infty$ in Hilbert spaces where F is the operator that maps (a description of) an admissible scatterer q to the far field

u_∞ of the corresponding scattered field. It has been shown in recent papers that F is Fréchet differentiable and that the derivative can been characterized as a boundary value problem. This opens the possibility to apply (regularized!) Newton methods to find an approximation to the exact solution q^+ given an initial guess q_0 and noisy data with known u_∞^δ error bound $\left\| u_\infty^\delta - u_\infty \right\| \leq \delta$. A critical problem in iterative methods for ill-posed problems is the choice of the stopping index. We take the first index $N = N(\delta, u_\infty^\delta)$ for which $\left\| F(q_N) - u_\infty^\delta \right\| \leq \tau\delta$ with some fixed constant $\tau > 1$. We show that for any sequence of noisy data $u_\infty^{\delta_n}$ with $\delta_n \to 0$ we have $q_{N(\delta_n, u_\infty^{\delta_n})} \to q^+$. It is well known that this convergence can be arbitrarily slow unless a source condition is fulfilled which for nonlinear problems usually has the form

$$q_0 - q^\dagger = f(F'[q^+]^* F[q^+])\omega.$$

We show that with the usual choice $f(t) = t^\upsilon$, $\upsilon > 0$ this condition is far too restrictive for inverse scattering problems. It turns out that with $f(t) = (-\ln t)^{-p}$ the source condition can be thought of as a smoothness and closeness condition in Sobolev spaces where p corresponds to the index of the Sobolev space. Then under additional assumptions

$$\left\| q_{N(\delta, u_\infty^\delta)} - q^+ \right\| = O((-\ln\delta)^{-p}), \ \delta \to 0$$

anf for exact data ($\delta = 0$)

$$\left\| q_n - q^+ \right\| = O(n^{-p}), \ n \to \infty.$$

These theoretical results are confirmed by experiments with the above and other inverse scattering problems in two space dimensions.

Neural Network Architectures for the Estimation of Conductivity Profiles of Layered Structures in Eddy Current Nondestructive Testing Applications

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The inversion of eddy current probe measurements has a significant impact on the characterization of material properties and the estimation of their geometric distributions. The evaluation of the conductivity profile of layered conductive structures belongs to this class of impedance inversion problems. Actually, it attracts a lot of interest in nondestructive testing applications, such as the detection of corrosion and the estimation of the thicknesses of metallic layers.

In this paper we investigate the possibility of developing neural networks that will perform the inversion of impedance measurements in eddy current testing of layered conductive structures. The application of neural networks to this kind of problem is based on their attractive property of being universal mapping approximators. In this work we examine two different neural network architectures. The first is a feed forward multilayer perceptron trained by means of the backpropagation learning algorithm. The second is based on the radial basis functions. In this case, two different training strategies have been implemented that are related to a gradient optimization scheme and the orthogonal least squares algorithm respectively. In contrast to the gradient based training, the orthogonal least squares algorithm is suitable for an optimal construction of radial basis functions neural networks.

The above architectures and training processes have been applied to two problems. The first involves a single conductive layer of known conductivity. The networks have been trained to identify the unknown thickness of the layer and the lift - off of the probe coil. This application simulates the estimation of the thickness of a conductive plate covered by a nonconductive coating. The second application examines a structure of two metallic layers of known conductivity that are separated by air. This simulates a double layer skin of an airframe. The networks have been trained to identify the thicknesses of these two layers. In these two examples, the inversion has been based on simulated data that have been obtained by use of a variety of excitation frequencies. The performance of the proposed architectures is compared and their robustness in the presence of noisy data measurements is examined.

A Neural Electromagnetic Approach to Object Identification

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A large number of electromagnetic inverse scattering problems deal with the identification (either by analyzing a "signature", or by reconstructing the unknown dielectric characteristics) of an unknown body inside an investigation domain, whose features are equally not available. This approach have been used, for instance, for radar target identification purposes and for the dielectric characterization of the earth subsurface by Ground Penetrating Radar (GPR).

To the aim of a faster and more reliable result to this problems, many approaches have been proposed in technical literature, mainly based on the numerical inversion of the integral scattering equations for the given problem geometry in a spatial domain. In this context, the usual simplification made in the approach is to consider cylindric structures, because in this situation the 3D problem simplifies to the characterization of a 2D section of the ground. Recently, alternative proposal to face also nonlinear inverse scattering problems have been introduced that employ minimization techniques both deterministic, and probabilistic ones. However, all these methods generally are complex and cpu-intensive.

A faster approach may be based on neural networks, that as for now have been employed only for the detection and classification of buried mines. As well-known, a neural network is a computer model attempting to mimic the behavior of the human brain by combining the capabilities of very simple computing nodes (that correspond to brain neurons). The big advantage of neural networks is that they are completely general tools, and, if suitably tailored to the given problem, they may give faster and similarly exact solutions to the approximation problem than more traditional methods. Many different neural networks have been proposed in literature: the great number of possible architectures allows to choose the most suitable structure for a given problem. However, a two-layer feed forward perceptron network with a noncostant, bounded, and monotone-increasing activation function is sufficient to approximate any nonlinear function $\mathbf{Y} = f(\mathbf{X})$ relating the two sets of variables $\mathbf{X}$ and $\mathbf{Y}$ (*universal approximation theorem*).

By using such a perceptron scheme, we developed a numeical approach to detect unknown objects inside an investigation domain by starting from the knowledge of the electric field scattered around it.

First we investigated the problem of a TM wave interacting with an unknown circular cylindric body in an homogeneous media: by the scattered electric field collected in N points located in the outer space, we were able to determine the location and the dielectric characterstics of the cylinder after a suitable training step in known situations. The absolute and relative errors were computed for each variable, allowing to test the robustness and relaibility of the approach, and giving satisfying results.

Second, the more complex situation of an inhomogeneous half space, with field collection points in the other half space, has been faced. Also in this case a suitable forward model was developed, and the geometric and dielectric characteristics of the unknown object were retrieved with good accuracy. The results obtained are very promising: for instance, when considering the cylindrical structure shown above we are able to detect the object with a mean precision of around 4, 3, and 4.5 % in position, radius and dielectric constant respectively.

Third Order Statistical Characteristics of the Surface Shape in Radar Remote Sensing of Sea Surface

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It is well-known that some large-scale sea phenomena (such as stream boundaries, stream interacting with sea-bed irregularity) manifest themselves at the sea surface by modifying the short-wavelength part of surface oscillations while the waves in the long-wavelength part of the spectrum remain unchanged. Thus the ripple energy variation map may tell about the physical processes taking place in the sea depth. For the development of the data processing procedures for remote ripple energy measurements in the presence of much larger surface waves, an adequate sea surface model on which the procedures will be tested is a key problem. Usually the surface ensemble is modeled on the basis of some surface spectrum while phases of the spectral components are assumed to be randomly distributed. This work proposes some extra surface (ensemble) parameters based on the surface bispectrum and thus involving the surface wave phases into consideration. With these parameters the simulation of nonlinear wave processes leading to, e.g., surface skewness and ripple modulation becomes possible. The new parameters characterize the surface shape in various wavelength bands. The relation between these surface parameters and the backscattering cross-section is investigated by means of computer simulation involving small-slope approximation. No evident relation between the averaged backscattered signal and the third-order longwave surface characteristics was found. This means that the observed asymmetry of the large waveforms cannot account for the upwind-downwind radar backscattering asymmetry. On the contrary, such relations were found for the bispectral characteristics in resonant surface wavelength band. The latter points out that the small-scale processes such as shortwave blockage can be more important for the backscattering.

Session C06
Thursday, July 16, AM 08:40-11:20
Room I
Hybrid Methods in Electromagnetism

Organiser : P. F. Combes
Chairs : P. F. Combes, W. Tabbara

Time Domain Hybridation of UTD and FDTD

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This paper deals with three tries of hybridation between an asymptotic method, namely the uniform theory of diffraction (UTD) and a so called exact formulation numerical method, namely the finite differences time domain (FDTD).

Asymptotic methods are only used when the dimensions of the object which is illuminated by an electromagnetic wave is large in comparison with the wavelength.

Conversely, FDTD cannot be used with structures which are larger than a few wavelengthes.

The translation in the time domain of these two properties is as followed.
For a given structure and a given impulsionnal excitation, asymptotic methods allow to compute correctly the high frequency response, wehereas FDTD allows to compute the low frequency response.

This paper proposes three methods to combine UTD and FDTD in order to obtain the complete response of a large structure to an impulsional electromagnetic wave.

The first one uses a spectral decomposition of the exciting wave in two parts : a low frequency spectrum and a high frequency spectrum. Each part is then treated with the more adequate method : either UTD or FDTD and the whole impulsionnal response is reconstructed.

Several examples will be presented in order to show the interest and the validity of such a technic.

The second one deals with the study of boxes which are illuminated through an aperture. We shall show that for a such problem, the field inside the box may be computed using FDTD, whereas the field outside the box may be computed using a correct hybridation of UTD and FDTD. We shall present a typical situation of this problem and we shall compare the results of the hybridation technic with a whole FDTD solution. Two kinds of result will be presented. One with the aperture in the shadow area and the other with the aperture in the lighted area.

The last one shows a DFDT/UTD hybridation on large structures allowing to take into account small geometrical details on its surface. We are now developping a method which allows to dissociate the source *(high frequency or low spectrum)* according to the illuminated structure's part.

In conclusion, we shall develop the main interesting aspects of these hybridations technics in terms of memory size and time calculation.

Analysis of Wideband Coupling to a Cavity : A Hybrid Integral Equation / Statistical Approach

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Prediction, over a wide frequency band, of the amount of electromagnetic energy coupled to one or more objects placed inside a cavity like enclosure with holes in its walls is an important topic in EMC applications. The energy coupled to the above structure depends on a large number of factors such as the dimensions of the structure, the frequency, direction of propagation and polarisation of the incident wave as well as the position of the scatterers. The analysis of an observable (fields, current, voltage, energy...induced by the coupling) conducted over the ranges of all or part of the factors, leads to a high cost in terms of computing time when achieved by means of exact methods (Integral equations, FDTD...). There is a need for models that allow evaluation of coupling levels at a less computational cost. We have chosen to address this problem by means of a hybrid approach which combines an integral representation of the fields with a statistical model of the observable.

Combining the equivalent dipole method for the aperture and an integral representation of the fields inside the enclosure, based on the dyadic Green's function of the cavity, we have computed the currents induced on cables and plates by means of a method of moments. We have achieved considerable gain in computational time by means of a rational function interpolation over a wide frequency band, either of the impedance matrix elements in the method of moments or of the observable. In the former case, the nodes of interpolation are uniformly placed between the analytically computed resonant frequencies of the empty cavity. In the latter case, a particular attention has been devoted to the relation between the number of available data points and that of the resonances of the observable that can be retrieved.

The cost-reduction problem can also be looked at in a somewhat unusual manner, at least as far as electromagnetics is concerned, if one takes the following considerations into account :

1- The observable is not equally influenced by all factors. It is then possible to call on some specific tools in data analysis to select the main factors and consequently neglect the others. This will lead to a significant reduction of the cost of computation and experimentation.

2- The knowledge of the fine variations of the observable with respect to the factors is not always necessary for the understanding of the phenomenon one is investigating. Consider, for example, the voltage induced at high frequencies by an electromagnetic wave at one end of a wire placed inside a cavity. The density of the resonances in the voltage increases with frequency and it is not generally possible to trace back the origin of these resonances. The determination of the trend of the voltage, or its maximum value over some frequency band, may then be a sufficient information.

In order to achieve the above stated goals, a multi-factor, parametric approach to system modelling, called Kriging is associated with the integral representation. It is shown that this method can lead to adequate prediction, together with an estimation of the accuracy of the predicted values of an observable. This is an efficient tool to bring out trends and also indicates where exact computations should be done.by means of an integral representation or any of the so called exact methods.

The main features of the integral representation and of the Kriging will be presented and discussed. A number of examples will be considered and the computed results compared with those obtained from measurements.

Antenna Analysis Using a Combination of the Finite-Element Method and the Geometrical Theory of Diffraction

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The finite element method (FEM) presents the advantage of being able to characterize precisely structures having complex geometries and to take into account dielectric losses. But costs in term of memory space and calculation times make this method inapplicable for structures of large dimensions compared to the wavelength.
To study such structures, asymptotic methods as the Geometrical Theory of Diffraction (GTD) are better adapted.
But, a lot of electromagnetic devices are composed of small and large objects compared to the wavelength, and in these cases neither a rigorous method nor an asymptotic one are efficient. Therefore it is necessary to adapt the method of analysis to characterize such devices.

In this paper a technique combining the FEM and the GTD method is presented to determine the radiating characteristics of antennas. To benefit of the advantages of both methods, the problem is divided into two subdomains. The first one includes the small part, and is analyzed by FEM using edge elements in the frequency domain [1]. The second one only contains the large part, and the diffraction on their edges is analyzed by the GTD method.
The first step is to determine the radiation in free space of the elements treated by the finite element method. For this purpose, a decomposition of the fields on spherical harmonics is used [2]. This method to determine the radiation in free space presents two important advantages compared to those using Absorbing Boundary Conditions [3]. Firstly the system to be solved remains sparse. Secondly this treatment is rigorous, it allows the boundary surface to be chosen close to the studied structure.
The radiation characteristics of the whole structure is then determined by calculating the diffraction of the previously determined fields in the second subdomain.
A test case of a wire antenna placed in front of a large but finite plane is presented.

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Comparison of Hybridization Methods between MoM and Asymptotics for Wire Antennas Radiation

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Radiation problem of an antenna close or attached to a metallic structure can be solved rigorously using Method of Moments (MoM), at the cost of large computational effort and within obvious size limits (a few wavelengths). It may be solved as well with asymptotic techniques based on currents distribution like Physical Optics (PO), or on rays like Uniform Theory of Diffraction (UTD), which include geometrical optics, with great savings in computational effort. But they may lack accuracy because they rest on an a-priori knowledge of the current distribution on the wire antenna. Self-consistent hybrid methods are then the most appropriate way of dealing with such problems. This presentation is focused on MoM-UTD and MoM-PO : after expounding their implementation in the illustrative case of wire antennas and a perfectly conducting plate with junction or not, we will present some results for monopoles and dipoles.

MM/UTD hybridization : Standard MoM for wires using pulse basis functions (BF) is used to solve the Electric Field Integral Equation (EFIE) and derive the impedance matrix $[Z^{MoM}]$ of the wire antenna alone. Interaction with the large object is accounted for by two other matrices $[\Delta Z_{mn}^{ref}]$ and $[\Delta Z_{mn}^{UTD}]$ for which entries ΔZ_{mn}^{ref} and ΔZ_{mn}^{UTD} are related to the electric field radiated by BF n, then respectively reflected and diffracted by the large body and at last tested by the BF m. Currents on the wires, i.e coefficients of the BF, are computed using :

$$[I] = \left[Z^{MoM} + \Delta Z^{ref} + \Delta Z^{UTD} \right]^{-1} [V]$$

where [V] is the incident field tested by BF m.
Radiation pattern is further deduced by UTD using the above results.

MM/PO hybridization : The whole structure is discretized on adequate basis functions for wires, surfaces and junctions. The entire structure is divided into two parts :

- A first zone where the EFIE will be written. It includes wires, junctions and a circular disk of radius R_1 around them as well as, close to the edges, an outer band of inner size $2R_2$.
- A zone where current densities will be deduced from the MoM unknowns through the physical optics approximation and injected in the EFIE.

Radiation pattern will be deduced by integrating all currents on the structure or by UTD.

Conclusion : Both hybridization techniques MoM/UTD and MoM/PO give accurate results in general, with lots of reduction in mass storage and computation time in the first case with respect to the second one, at the cost of software complexity.
The first technique is well appropriated for the case of a dipole over a flat metallic plate, whereas the second technique is more suited for the case of a monopole attached to the metallic plate. In both cases, the radiation patterns computed by UTD are in good agreement with these of MoM.

Hybrid Methods for Radar Coverage Forecasting

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The combination of parabolic equation (PE) models with ray-tracing provides accurate and fast computation of radar coverage in very large domains, typically several hundreds kilometres in range and several thousands metres in height. We use novel hybrid techniques which remove the restriction that the transmitting antenna should be inside the parabolic equation domain. This involves the use of incoming energy boundary conditions at the top of the PE domain to account for sources outside that domain. A generalised horizontal PE algorithm is used to extend the coverage diagram to large heights.

When the transmitter is outside the vertical PE domain, ray-tracing plays a crucial role both in computing the incoming energy field and in extending the results upwards. One of the interesting features of this technique is that there are no constraints on the refractive index structure used for the ray-trace below the "feeding-in" region. We show how to optimise this choice in order to minimize computational difficulties. In addition, suitable filters are used to avoid discontinuities in the ray-trace calculations due to diffraction effects close to the horizon.

Computation times for the resulting hybrid model remain of the order of a few seconds on a desktop computer even for demanding cases involving very high airborne transmitters. Comparisons with "pure" PE results show that accuracy is excellent while the gain in computing resources is often very large in both memory and execution time. Complex environments can be modelled, including range-dependent refractivity structures and irregular terrain with variable impedance. Surface roughness effects are taken into account with a generalised mixed transform method which avoids the computation of local incidence angles.

Comparison between a Rigorous and two Asymptotic Methods for the Calculation of the Lateral Surface Wave in VHF Propagation Channel

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Propagation in the presence of a plane boundary between two dielectric half spaces is a classical problem when dealing with the calculation of radar coverage as well as mobile communications. Different methods may be used to solve the problem, depending on the heights of the antennas, the nature of the ground and the accuracy required in the results. The existence of a surface wave should be taken into account when computing the signal amplitude if both antennas are located near the interface. In this case, it is known that the direct and reflected rays of Geometrical Optics (GO) yield incorrect results.

King (Lateral Electromagnetic Waves, Springer-Verlag New-York, Inc. 1992) recently proposed a single set of asymptotic formulas valid everywhere for electromagnetic waves generated by a vertical electric dipole near a plane boundary. The only condition is the requirement that the ratio of wave numbers ground to air be quite large. The advantage is to remove the restriction of previous asymptotic formulas (Banos) limited to nonoverlapping near-, intermediate-, and far-field ranges.

However, King proposed a far-field approximation to the asymptotic formulas that seems to be incorrect in cases we are interested in, thus leading us to review his simplifications and propose a new calculation for the asymptotic formulas; these formulas are valid for all points except very close to the dipole. The found approximation shows good agreement with the rigorous field computation that we perform using a software developped in our laboratory based on the calculation of Sommerfeld's integrals, and speeds up significantly calculations. Numerical results in VHF over different media using the rigorous method, King's far-field approximation and our asymptotic calculation are compared.

In the context of aeronautical VHF data link, it is important to predict the budget link on an airport for a mobile on the ground, hence surface wave has to be evaluated. As an experiment for VHF data communications system, measurements on Toulouse Blagnac Airport were realised at the frequency 118.025 Mhz. Both antennas were near the ground (at about three meters). Power level and Differential GPS position were simultaneously registered at the mobile receiver. Good correlation is obtained between experimental and theoretical results using our asymptotic calculation.

Diffraction of an Electromagneticgnetic Wave on a Target in an Heterogeneous Environment Application to Low Altitude Radar Detection Above the Sea Surface

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Radiowave propagation in a naval environment is strongly influenced by effects such as multiple scattering on sea surface and refractive index variations, which can produce a non negligible variation of the radar cross section of a target situated above the sea surface. In the literature, articles can be found about electromagnetic diffraction in the case of a non planar incident wave front but the particulars phenomenons induced by the sea presence are not taken into account. The objective of this study is to elaborate a computation methodology for electromagnetic diffraction by a target at low altitude in a naval environment.

The solution chosen for this problem is an hybridization of two methods : the Parabolic Equation method (P.E) for the computation of electromagnetic wave propagation in a realistic environment and the Plane Wave Spectrum scattering method (P.W.S.) which allows one to compute backscattering by the target whatever the incident wave front. The problem is decomposed in three parts : propagation from the radar to the target evaluated by the P.E. method, backscattering on the target performed using the P.W.S. method and the return path back to radar computed by the Parabolic Equation method.

The P.E. method is elaborated from the Helmoltz equation, with the hypothesis of paraxiality and azimutal symmetry. Solving it step by step along the propagation direction, one can compute the electromagnetic field on the target taking refractive index variations and boundary conditions on the sea surface into account. We apply the P.W.S. method to perform the backscattering by the target. The calculation is achieved in five steps :

(1) Find the incident wave spectrum, using a FFT of the incident field
(2) Propagate this spectrum to the target (multiplying by a phase term)
(3) Compute the scattered spectrum which equals the product of the incident wave-spectrum function by the bistatic scattered coefficient
(4) Integrate the resulting function over the incident wavenumbers
(5) Determine the backscattered field from the scattered spectrum using an asymptotic expression.

The target is characterised by its bistatic scattering coefficient ; for our tests canonical targets of infinite length as a cylinder or a wedge have been considered.
The backscattered field computed using the P.W.S. scattering method becomes the incident field of the P.E. resolution in the evaluation of the return path.

First, the hybridization of the two methods has been validated in simple configurations (canonical targets in standard atmosphere and with a smooth sea surface) : the results are compared to analytical formulations based on G.T.D. in the case of the wedge or a Bessel-Hankel decomposition in the case of the cylinder. Then we demonstrate that our method is able to work in more realistic configurations including evaporation duct effects or scattering on a rough sea.

Session D06
Thursday, July 16, AM 08:40-11:40
Room 120
Iterative Methods in Scattering

Organisers : H. Baudrand, F. Obelleiro
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Iterative Integral Approaches to Study Radiation and Scattering from Bodies Modelled by Parametric surfaces

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This communications presents a review of integralapproaches to determine the radiation and scattering of electrically largeconducting structures. The shape of these structures can be completelyarbitrary, this degree of flexibility is attained by modelling the surfacewith parametric patches called NURBS (Non Uniform Rational B-Spline) [1].Due to the characteristics of the analyzed bodies, closed and smooth, thedifferent approaches solve the MFIE (Magnetic Field Integral Equation) discretizing the electric current density $\vec{J}$ s22 over the surface by means generalized rooftops [2]. In thediscretization of the MFIE a new razor blade has been developed.

One of the main features is the application of the *dipole moments approximation* [3] to calculate the couplingfactors among all the current rooftops. This technique simplifies theevaluation for the operator applying closed expressions in terms of vectors called*electric dipolemoments*. This operation way is veryfast and the matrix elements are not stored. This is one of the keys of thedeveloped techniques.

About the electromagnetic method, the MFIE is solved followingdifferent iterative algorithms in order to see which one presents the bestperformance in convergence and results. There are two groups of techniques:one follows the MFIE as it is defined, and the other iterates under thescheme of the Conjugate Gradient Method [4] minimizing the magnetic fieldinside the conductor body. Physical Optics current has been included toobserve if the convergence is enhanced.

Satisfactory results have been obtained when they are comparedwith measurements and with other integral rigorous methods, such as theMethod of Moments. An improvement near of 50% in CPU time is achievedrespect to the Method of Moments. With respect to memory, the improvement iseven better; the decrease in memory requirements can reach the 99.5% for astructure with electrical dimensions. As the electrical size of the body grows, thememory improvement attains higher values.

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Iterative Solutions of the MFIE for Computing the Electromagnetic Scattering of Large Open-Ended Waveguide Cavities

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The presence of jet engines greatly influences the overall electromagnetic scattering response of realistic targets. Therefore, the development of accurate and efficient methods for analyzing high-frequency scattering from electrically large open cavities has become an important task, which is addressed in this talk. A magnetic field integral equation (MFIE) for the equivalent currents on the interior cavity walls is obtained and solved by two different algorithms based on high frequency principles of *Physical Optics* (PO): The *Iterative Physical Optics* (IPO) [1] and the *Progressive Physical Optics* (PPO) [2]. Once the currents are known, the scattered fields are obtained by using *Aperture Integration* (AI) in the cavity mouth or *Reciprocity Integral* (RI) over a surface close to the termination [3,4]. These methods provide a significant improvement with respect to previous ray and beam methods [5]. Nevertheless, their computational cost increases as the cavity becomes deeper (mainly for IPO method), and consequently its efficiency highly depends on the cavity shape. In order to enhance their scope of application to deeper cavities, an efficient segmented approach is also presented in this talk. The entire cavity is split into sections which are analyzed independently. The response of the whole cavity is obtained by cascading the individual transmission matrices via a simplified *connecting scheme*. This process requires much less computational cost than the direct solution of the whole cavity, while maintaining a high degree of accuracy. Numerical results are presented which demonstrate the convergence and accuracy of the proposed methods by comparison with modal reference solution.

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On the Use of Iterative Selection of Wavelet and Wavelet-Packet Basis Functions in the Method of Moments

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The use of wavelet and wavelet packet expansions in numerical solutions of electromagnetic frequency-domain integral equation formulations is steadily growing. In this talk we will review the use of iterative selection of wavelet and wavelet-packet expansion functions for compressing the moment method impedance matrix. The expansion functions are selected from a dictionary which may also be overcomplete. The iterative procedure facilitates a systematic selection of the few expansion functions which can adequately span the unknown current to a given accuracy. Considering only these dominant expansion functions, a substantially smaller number of coefficients has to be determined. A few numerical results will be included to show the advantages offered by this approach and to demonstrate that a restrained growth in the number of unknowns can be achieved even when on the face of it there is an increase in problem capacity.

An Iterative Solution of the Combined Field Integral Equation

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An iterative method based on the *combined field integral equation* (CFIE) [1], avoiding the inversion of the *moment method* (MoM) matrix, is presented in this talk. The solution is obtained as a Newmann series with a relaxation parameter [2], which is included in order to obtain important computational advantages. A critical feature of the method, is the choice of the relaxation and CFIE parameters, because, as will be shown, a poor choice of them could produce even a divergent sequence. Intensive numerical tests have been performed in order to obtain empirical rules, which allow to obtain adequate values for the parameters. Several results, comparing this approach with other well-known iterative methods, such as the *Conjugate Gradient* method [3], are presented in order to verify the efficiency and accuracy of the proposed method.

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Domain Decomposition and Iterative Methods in Electromagnetics

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"Divide and conquer" is a known concept to solve Maxwell equations in microwave structures either guiding or radiating ones. It inspires many methods which could be seen as domain decomposition like methods. It allows to tackle the complexity involved in the modeling of electromagnetic systems. Less known or obvious is the complexity related to the solution of Partial Derivatives Equations (PDE) which is overcome by using techniques like Finite Element or Finite Difference Methods. The PDE are converted to an finite linear system by decomposing the space into many elements or cells in which the fields can be expanded in terms of simple polynomial functions. More known is the complexity related to the solution of the linear system especially those encountered when characterizing large structures compared to wavelength that cannot be handled in one piece. The whole space is then decomposed in domains. Each domain is advantageously characterized separately. The next step is to recombine the several parts by using the continuity of the fields across the common boundaries. The efficiency of the recombination relies on the algorithm used for this purpose. Iterative techniques are the only practicable ways to deal with real world problems.

Among iterative methods, the one based on the concept of waves is very interesting. This iterative process provides useful physical insight which further gives numerical efficiency. This process may be compared to similar domain decomposition methods. As a concept, it can be very simply explained with the help of a circuit network which is the discrete counterpart of the Maxwell equations. In this way, diakoptics techniques are also strongly related to domain decomposition ones. The wave concept is not restricted to volume or differential methods, it can also be seen and used in conjunction with integral methods. More generally, it gives an intuitive and efficient way to realize the electromagnetic coupling between several parts of a system. The different possible points of view on domain decomposition and iterative methods will be reviewed and compared. The physical and numerical issues will be discussed.

Applications of Wave Concept in Planar Circuits

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The concept of Waves is very interesting in the problems of diffraction where the empty space presents analytic eigen functions for the green operator. It is the case of the planes cylinder and spheres especially for the plane the Fast Fourrier Transform gives easily the modes TE and TM of a rectangular geometry which is the case of planar circuits the boundary condition are translated in terms of amplitude of waves by the formulas.

$$A = \frac{1}{2\sqrt{Z_0}}(E + Z_0 H \times n)$$

$$B = \frac{1}{2\sqrt{Z_0}}(E - Z_0 H \times n)$$

The paper presents some applications such that coupling between localized sources, air briges and discontinuities, and shows the interest of this concept for an important reduction of computation time.

Modeling of Electromagnetic Waves Propagation in Heterogeneous Structures by Using an Iterative Method

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The knowledge of the propagation in heterogeneous structures is necessary to optimize the properties of composite materials. Usual mixture laws or homogeneization method generally fail when the inclusion sizes are of the same order as the wavelength λ. The failure of this approach is especially observed in the millimetric frequency range where it is no more possible to neglect the coupling effects due to the multiple scattering between the particles.

The heterogeneous structures looked upon in this paper are 3D networks made with a finite number of spheres or infinite cylinders. We present a model allowing us to take into account the multiple scattering effects by using an iterative method. The general wave propagation equation is first solved in the case of a single particle, using the Mie theory. Then, in the case of N inclusions, we calculate the first order scattered field which results from the excitation of each particle by the incident wave alone. The second order scattered field, as for it, results from the excitation of one sphere or cylinder by the first order field scattered from the remaining N-1 ones. This iterative process continues until a stop criterion is satisfied. The total scattered field is the sum of all the contributions.

Numerical limits of the process are discussed. Possible applications of this method are shown in the domain of Radar Cross Section or material conception. Computational results are compared with the litterature and with free-space measurements from 4 GHz to 110 GHz.

The Wave Concept Iterative Process Applied to Study Arbitrary Shaped Radiating Structures

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Hybrid Finite Element method/Boundary Element method formulation is successively used to solve radiation and scattering problems [1]. The structure to be studied is included within a closed surface on which the BEM is employed, and the FEM is used in the volume limited by this surface. The core region which can contain inhomogeneous isotropic or anisotropic dielectric materials is best modeled by FEM, while the outer region and the implied radiation condition is naturally taken into account by BEM. The resulting problem can be directly solved, but several computational disadvantages arise : mainly this system is of high order, and the system matrix to be solved is partly sparse for the part relative to the FEM, and partly full for the one resulting from the BEM.
In order to reduce the size of the system to be solved and to keep the computational characteristics of systems resulting from the FEM and BEM independant, it is interesting to solve separately the interior and the exterior problems. An iterative resolution method allows us to treat successively the two domains. The results obtained in each domain will be taken into account in the other one by the use of new vectorial waves functions.
Let V be the domain including the studied radiating structure, and S be its boundary surface. Waves are defined on the surface S as [2] :

$$\vec{A}_S = \frac{1}{2\sqrt{Z_0}}\left(\vec{E}_t - Z_0 J\right), \qquad \vec{B}_S = \frac{1}{2\sqrt{Z_0}}\left(\vec{E}_t + Z_0 J\right),$$

where $\vec{J} = \vec{H} \times \vec{n}_S$

$\vec{n}_S$ is the outward unit vector on S

Z_0 is the wave impedance in free space

The iterative process is as follows :
At the first iteration, we take $\vec{B}_S^{(0)} = \vec{0}$. The resolution of the interior problem leads to the determination of $\vec{A}_S^{(0)}$. This results is reemployed to solve the exterior problem and we thus determine $\vec{B}_S^{(1)}$.
At the Nth iteration, $\vec{B}_S^{(N-1)}$ is known, and the resolution of the interior problem leads to $\vec{A}_S^{(N-1)}$. With the exterior problem we then find $\vec{B}_S^{(N)}$.
The properties of the operators involved show that this process is always convergent.

In the special case in which the surface S is a sphere, the exterior domain can be easily solved analytically. For this purpose, we expand the fields in the exterior domain on spherical harmonics. For each of these modes, the simple analytical relation between A and B waves exists. This allows us to solve the exterior problem without employing the BEM. This case is computationally very interesting, because we only have to solve the FEM problem, and the convergence is very fast : 3 iterations are enough.

Results are presented for a test case of a patch antenna, in which a non spherical border surface is used.

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Session E09
Thursday, July 16, AM 08:40-11:20
Room K
Domain Decomposition, Segmentation and Hybridization Methods for Modeling Microwave Structures

Organiser : M. F. Wong

Chairs : M. F. Wong, W. C. Chew

Some Domain Decomposition Related Methods in Computational Electromagnetics

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Domain decomposition (DD) is often used to reduced computational labors in solving a problem, for example, in finite element method. In this talk, we will review several domain decomposition methods where computational labors can be reduced.

One is the numerical mode matching method, which is related to the method of lines. This method is particularly suited for solving waveguide junction problem, where long sections of waveguides are punctuated by junctions. Boundary conditions are imposed at waveguide junctions to obtain reflection and transmission operators, where mode conversion physics are accounted for.

Another DD related technique is the nested equivalence principle algorithm (NEPAL). This is an integral equation solver whereby volumetric scatterers are replaced by surface scatterer in a nested fashion. Hence, long-range interaction between groups are computed via only surface scatterers resulting in reduced computational load. The computational complexity for inverting a matrix is $O(N^{1.5})$ in 2D and $O(N^2)$ in 3D. This method is related to the nested dissection ordering method in finite element.

A wavelet technique can be considered a DD technique in the abstract vector space spanned by the wavelet basis, where high-spatial frequency wavelets are separated from low-frequency wavelets. High-frequency wavelets interact with each other weakly, and hence results in dramatic sparsification of the wavelet transformed matrix that results from the method of moments.

The boundary integral equation technique is related to the DD technique whereby solutions in two or more domains are first solved analytically or numerically (e.g., with finite element), and then pieced together with boundary integral equations. These boundary integral equations yield dense matrices. However, the recent advent in the multilevel fast multipole algorithm allows such dense matrices to be solved efficiently.

We will also describe a DD related technique for solving for scattering from a large engine inlet. Due to the near resonance of such a structure, such a scatterer requires a large number of iterations to solve. By sectioning the scatterer, and recursively obtaining the admittance matrix of the engine inlet, the number of iterations required to solve the scattering problem can be greatly reduced.

A Domain Decomposition Method for Maxwell equations in the frequency domain

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We will first recall the basic idea of the non-overlapping iterative domain decomposition method first introduced in [1] for coercive elliptic problems and extended to the Helmholtz equation in [2] [3]. For these equations, the key point is the use of Robin-type transmission boundary conditions with a complex non real coefficient. We also present some variants of this method including the extension to Maxwell's equations, the use of relaxation algorithms and non-local transmission operators. Applications of this method to various wave propagation problems will be presented.

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Combined Iterative-Subdomain Method in Planar Circuits

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The iterative procedure based on the concept of waves have application in problems of diffraction [1], and in planar circuits [2]. The procedure in this case needs the systematic utilization of Fast Modes Transform and the inverse. In this paper it is shown that the convergence of the method is improved by a linear combination of the results given by the preceding iterations however, when an important accuracy is necessary rather than using a great number of pixels which increases the duration of each iterations it is often preferable to begin the process with a coarse definition and to finish with a precise mesh, each pixel of the coarse definition becoming a subdomain of the final mesh. Some applications of this procedure are given showing the efficiency of this method.

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Hybrid Electromagnetic Characterization of Microwave Modules

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The increase in the operating frequency, in the complexity and integration density of modern microwave modules and circuits, generate parasitic effects such as indirect interferences between radiant components, metallic enclosure resonances,... The segmentation approach, applied in classical commercial circuit simulators, can't permit to take into account these interactions.

Consequently, a rigorous and global electromagnetic analysis becomes essential to anticipate, limit and even cancel these descriptive phenomena, degrading the circuits performances.

A microwave module can be composed of different MMIC or hybrid circuits. The electromagnetic software must be applied to simulate the distributed part of the analyzed domain. Some distributed effects can intervene both in the circuits, or in their surrounding closed by the module external boundary. Some elements can however be considered localized for the characterization. We need then a CAD tool able :

- To take into account interactions between domains which dimensions differ significantly. We propose to apply a generalized matrix approach, which permits to characterize the different distributed parts of the analyzed volume independently from each other.
- To take into account in a same global analysis the presence of distributed domain and localized ones, which might be active and non linear. Different methods have been presented recently for this task. We have proposed to couple a finite element simulator to a circuit software. The electromagnetic formulation is solved in the frequency domain, and an harmonic balance technique is applied to obtain the response of the whole domain.

We will present the methodology of application of these different techniques, taking the example of a microwave module characterization.

Non-Reflecting Boundary Conditions for Guided Waves

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We consider time-harmonic waves propagating in a waveguide. Any standard solution procedure is based more or less explicitly on the characterization of the guided part of the wave from some special solutions called modes of the waveguide. Each mode is expressed in terms of the eigenfunctions of the transverse Laplacian on the cross-section S of the waveguide. Truncating the infinite part of the waveguide beyond S leads straightforwardly to a boundary condition on S involving these modes. This expression is nothing else but an explicit writing of the Dirichlet-to-Neumann operator, also called the Steklov-Poincaré operator. It is well known that it is not generally easy to handle such an operator from a numerical standpoint, the difficulty coming from their so-called non-local character. Another difficulty in the numerical approximation of the present boundary condition stems from the fact that the propagation in a waveguide can be multimodal and dispersive.

The most direct and natural approach for solving the problem consists in using a truncated expansion of the trace of the solution on section S. However this method requires the determination of the eigenfunctions, and the non-local character of the boundary condition remains present in the numerical scheme: all degrees of freedom relative to S are coupled together. The boundary condition which we propose uses a rational approximation of the Steklov-Poincaré operator, involving only the eigenvalues of the transverse Laplacian. Thus, eigenmodes are needed only if they are used to feed the waveguide or if reflection coefficients have to be calculated. This boundary condition is an extension of an impedance boundary condition valid for one propagating mode, which has been used for a long time in electrical engineering calculations. Though non-local, we call it a quasi-local boundary condition because the resulting boundary-value system involves only local, that is, differential operators when some adequate auxiliary unknowns join the formulation.

Although Padé approximations of the Steklov-Poincaré operator symbol have been considered for a long time, they have apparently not been used for waveguides yet. Previous derivations of absorbing boundary conditions use an approximation of this symbol either locally or globally, depending on the desired properties of the resulting scheme. In the present case, the approximation process is based rather on an interpolation of this symbol. In another context, a similar approach has been adopted by Bayliss and Turkel to write out a hierarchy of boundary conditions which annihilates successive terms in the Wilcox expansion of any solution to the two-dimensional wave equation in an exterior domain.

The quasi-local boundary condition is expressed in terms of partial derivatives of order no more than two. Accordingly, its effective numerical approximation can be performed through usual low order finite element schemes. It is perfectly transparent for the propagating or evanescent modes which are considered in the interpolation process, that is, it has the same effect on these modes as the exact boundary condition. This property is stronger than low reflecting because incident waves propagate through the boundary without perturbation. Although some auxiliary functions are introduced, a lumping process makes it possible to keep only the finite-element degrees of freedom of the solution as unknowns in the discrete problem. The matrix of the resulting linear system remains sparse everywhere and can be obtained through a standard assembly process. Numerical experiments confirm that the method is capable of effectively solving various problems in waveguides. They show a very low-level reflection of the incident wave, comparable to the one found by using Berenger's Perfectly Matched Layer in the solution of the problem by a finite-difference time-domain method.

Diakoptics Techniques in the FDTD Method

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Like other rigourous methods, the FDTD method necessitates large memory storage and long computation time when the size of the studied objects increases. For this reason, many efforts in the past have been previously made in different ways to handle this problem.

One can distinguish two kind of methods. The first ones can be named hybridation methods. The idea consists of taking advantage of the adaptability of several methods to deal with subproblems and to combine them to solve the hole problem. e.g., rigourous methods combined with asymptotics or integrals methods give powerful and elegant solutions of many important electromagnetic engineering. These methods are gaining more and more importance actually.

The other area of research are the methods related to domain decompostion techniques. Many ideas can be seen and handled under the concept of domain decomposition. It goes from the direct parallel implementation of an algorithm, to the use of circuit principles using different matrix in circuit theory, to pure electromagnetic theory like Green functions and so on.

For instance, **diakoptics** was introduced by gabriel Kron [1] to solve Maxwell's equations or other field problems in a piecewise manner, with a common framework derived from circuit theory. A time domain adaptation of the diakoptics have been introduced by P.B Johns in 1980 [2].

Time domain diakoptics technique consist in the computation of the subdomain numerical Green function. This numerical Green function namely called Johns matrix or Transfer function, ensure the continuity of the fields of the subdomain with its neighbours through the communications areas. The Johns matrix contains the terms giving the relation between input and output ports [3]. The domain reconnection is assured by convolution products in the time domain.

The main problem of this method is the large memory size of the Johns matrix, since the three dimensions of the matrix are the number of input ports, the number of output port, and the number of time steps. The last dimension is the most problematic one. We can accept limits in the size of the communication areas, but for the number of time steps, a limit will be more problematic.

A convenient solution for the reduction of the memory size that occupies the Johns matrix is the use of compression techniques by interpolation/extrapolation schemes. The GPOF (Generalized Puncil Of Function) method is one of this powerful method introduced by T. Sarkar [4]. The idea here is to decompose the Green functions on generalized eigenvalues and residues of the signals. This decomposition allows the interpolation and extrapolation of missing informations and the recursive formulation of the convolution product to speed updating it and to avoid extra memory storages.

Good results have been already obtained in one and two dimensions problems by the application of this concept. Results for the case of electomagnetic coupling of two cavities are presented.

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Increase of the Reduction Factor for Subgridding Approach in the FDTD Method

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The subgridding technique used in conjunction with the FDTD has been developed to locally improve the field resolution near objects with fine structures. This technique allows us to alleviate the burden of both time and memory requirements. The main advantage of the subgridding technique is that the local refinement of the mesh does not effect the rest of the computational domain.

In most of the subgridding algorithms described in the literature the reduction factor is limited. The purpose of this paper is to present a stable and accurate subgridding technique based on imbricated submeshes which allows us to obtain a high reduction factor of at least 16. We have used a new subgridding approach based on a scheme developed by Okoniewski [1]. To increase the reduction factor, we imbricate local grids one into another successively. This imbricated technique is based on two major upsets. The most important is the decrease of the error and the reflection coefficient involved when the cell size is reduced compared to the wavelength. The consequence is the reduction of the reflection coefficient from each added imbricated grid. The second upset is the use of standard FDTD transition regions between every two imbricated local grids which stabilizes the subgridding algorithm.

The presented technique has been analyzed and used to describe the field behavior near fine structures. The reflection coefficient due to the subgridding region is inferior to 1% for a reduction factor of 16 which corresponds to four imbricated local grids. Several examples such as scattering from a perfect conducting sphere have been analyzed to evaluate the efficiency of this subgridding approach, and the results will be included in the presentation.

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Session F08
Thursday, July 16, AM 8:40-11:40
Room B/C
Conformal and Smart Microstrip Antennas

Organiser : K. F. Lee
Chairs : K. F. Lee, R.Q. Lee

Varactor Diode-Loaded Polarization-Agile Antennas

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Square an circular patches with varactor diodes fitted symmetrically to the radiating edges can be made polarization-agile. When orthogonal modes are simultaneously excited by means of diagonally positioned feed point, the radiated polarization can be varied by the bias voltages on the varactor diodes.

When both orthogonal modes are resonant et the input frequency, the radiated polarization is linear in the diagonal plane, being the resultant of the two modes. In this manner of operation it is possible to make fine adjustements to the varactor bias voltages to reduce cross polarization to around - 30dB.

When the phase of one orthogonal mode is adjusted to be 45 degrees in advance of the input signal while the other is lagging by 45 degrees, circular polarization results, (left or right hand), and the axial ratio can be optimised by fine adjustment of the bias voltages. Boresight axial ratios typically better than 0.5dB ar obtainable and can be optimised byt fine adjustement of the bias voltages.

Linear polarization in the plane of either mode is obtained by suppressing the unwanted mode by setting the varactors controlling that mode to zero volts. Cross polarization under these conditions tends to be slightly higher (at around -20dB) than when linearly polarized in the diagonal plane. The input match in lineart states is typically much better than -15dB and better than -12dB in circular polarization, and with the additional facility to independently vary the bias on each diode rather than operating them in pairs, matching in all polarization states can be optimised. Bandwidths at any one single frequency setting are typically around 1 per cent, and with the frequency agility afforded by the varactors, it is possible to obain both circular and linear polarizations, with optimised input match and axial ratio, over a 2.4% frequency range.

The properties of both circular and square patch elements have been explored, and the square patch has been observed to give better radiation patterns. Afour-element linear array of square patches has been constructed and its performance with regard to cross polarization in the selected linear states, axial ratios in circular states, and input match, was similar to that of the elements themselves.

The polarization-agile patch is simple to operate manually when used to discrimate between two amplitude modulated signals transmitted both at the same frequency, but each using opposite senses of circular polarization, to carry different audio programmes. Rejection of the unwanted signal was better than -30dB. Forthermore, if the carrier frequency of the unwanted signal was varied by $\pm 1\%$, or if the axial ratio deviated marginally from 0dB, it was possible to maintain this level of rejection of the unwanted signal by fine adjustement of the varactor diodes with minimal loss of strength of the wanted signal.

EM Field Mapping Issues Related to Active Antenna Design

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With integrated high frequency antenna circuits becoming more important and widespread in their use, accurate simulation of electromagnetic field distributions in the presence of active devices is paramount to the successful outcome of a specific design and to the creation of new antenna topologies. This paper discusses a number of integrated antenna architectures and associated simulation issues. The first of these is a passive slot ring antenna: here mixed cyclindrical and cartesian co-ordinate systems together with network tearing strategies are described in order to facilitate the design using FDTD techniques. A comparison between simulated and measured behaviour is given.

Then an active slot loop antenna is described, i.e. the passive slot loop antenna above is used as the resonant load in a three terminal oscillator circuit. Here we have a class of circuit which is extremely challenging for computer simulation. The challenge occurs since the circuit exhibits all of the features required in a generic robust non-linear circuit/EM field solver. First it has both distributed and lumped/passive circuit features. Second it operates in large signal mode with a three terminal active device. Third it exhibits surface wave and free-space radiation coupling effects. Finally it has start-up transients which manifest themselves as a time dependent load attached to the active device terminals. Specially developed computational processes involving interacting EM field and large signal circuit simulators will be described which allow normal self-sustained oscillator circuit qualifying features such as output frequency to be quantified in addition to the usual EM predicted features such as antenna far-field radiation performance.

Applications of the approaches described above to three dimensional Silicon micromachined cavity backed active antennas will be given. The influence of the cavity structure on the active antenna's phase noise performance will be described and its potential use as an elemental building block in a spatial power combining array discussed.

Next a novel embodiment involving diodes directly incorporated into a microstrip patch antenna array which is capable of automatically tracking an incoming signal will be described in order to show how EM/large signal hybrid simulation aids in the development of new antenna architectures with added functionality.

A number of the problems involved in the physical realisation of such antenna structures on high resistivity silicon will be discussed. It will be described how the physics of the interconnection between the metallization and the silicon substrate can profoundly affect the microwave characteristics of the antenna structures. Processing countermeasures will be described and the resultant additional modelling complexity described.

Pattern Synthesis of Conformal Arrays by the Simulated Annealing Technique

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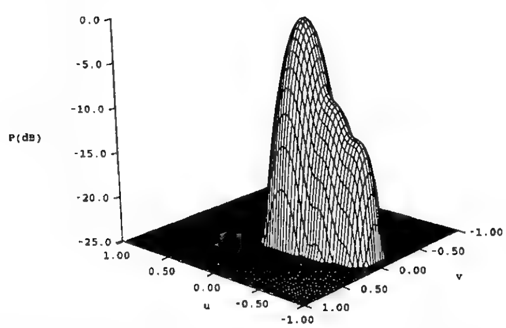
There are some applications for array antennas that require to conform the array over a specified shaped surface. If the application requires to provide 360 deg. in ϕ coverage, the array may be conformed over a cylindrical surface. When a good aerodynamic behavior is required the array may be conformed over a hemispherical surface. Both cases also allow to scan the beam electronically [1], however is necessary to take into account the expression of the element pattern in the optimization because each element is facing to a different direction.

We use the simulated annealing technique [2] to minimize a cost function which takes into account all possible parameters of interest in the pattern synthesis such as the sidelobe level, the beamwidth, the dynamic range of the excitations, possible positions of nulls, and any parameter that we need to control for synthesize a desired pattern [3].

Our method also allows to control the polarization of the radiation pattern, minimizing the crosspolar component and shaping the copolar component to a desired pattern.

The example below shows a cosec^2 radiation pattern synthesized by a cylindrical array with 8x8 axial dipoles. The obtained sidelobe level is -25dB, the -3dB beamwidth is 16°, the dynamic range $|I_{max}/I_{min}|$ was minimized to 3.5 and the average deviation is 0.3dB in the cosec^2 region.



Three dimensional pattern for an 8x8 cylindrical array.

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Radiation and Scattering Characteristics of Spherical Microstrip Antennas

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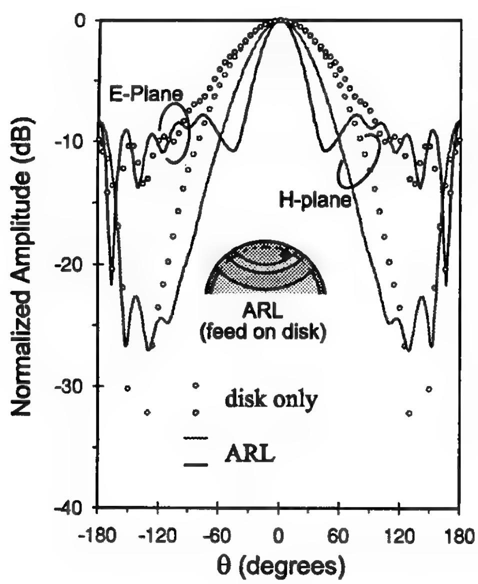
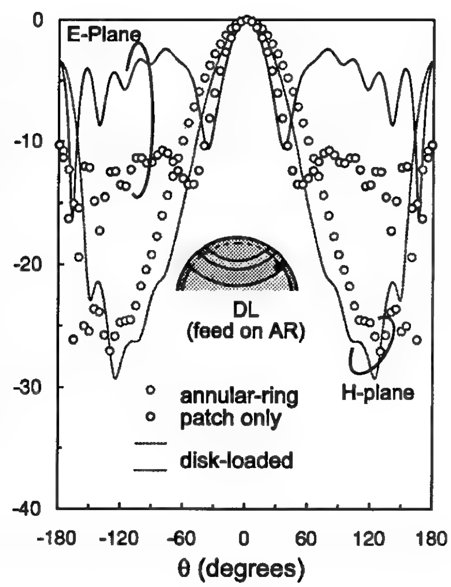
In this paper, the radiation and scattering characteristics of circular and annular-ring microstrip antennas on a spherical body are analyzed by using full-wave method. By comparing to the cavity-model analysis and generalized transmission line model (GTLM), the full-wave analysis, a Green's-function formulation in the spectral domain incorporating with a Galerkin's moment-method calculation, is applicable for thicker substrates and more rigorous for analyzing microstrip antennas. However, the computation of full-wave analysis is relatively more complicated and requires careful programming to be computationally efficient. As shown in the figure, a circular and an annular-ring patches are printed on the spherical grounded substrate. Such kind of geometry exhibits dual resonant frequencies. In general, one resonance is higher than that of single annular-ring patch case and the other is lower than that of disk only case. By adjusting the TM_{11} mode resonant frequency of the disk to be very close to the TM_{12} mode of the annular-ring patch, the antenna bandwidth can be broadened significantly. As for the radiation characteristics, both the annular-ring loaded spherical circular and the disk-load spherical annular-ring microstrip antennas are broadside antennas. However, by comparing to single patch case, the loaded cases have narrower beamwidth of main lobe and larger side lobes radiation. More numerical results of the cross-polarization and scattering characteristics of the spherical microstrip antennas are also calculated and will be presented at the meeting.





Coupling and Radiation Characteristics of Cylindrical Microstrip Arrays

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Mutual coupling between cylindrical microstrip antennas has been studied using theore-tical approaches based on the full-wave approach, cavity-model analysis, and generalized transmission line model (GTLM) method. The full-wave approach is rigorous and more accurate solutions are expected to be obtained. On the other hand, the cavity-model analysis and GTLM method are relatively simpler in the formulation and more efficient in the numerical computation. A comparison of the mutual coupling coefficients, obtained from the three different theoretical models, with the measured data will be given and discussed. The cases of cylindrical circular, rectangular, and triangular patches are studied.

For the full-wave approach, a set of electric-field integral equations is first derived, which is then reduced to a matrix equation using the Galerkin's procedure. By solving the matrix equation, the unknown patch surface current and the input impedance of the antenna can be calculated. Then, for the mutual coupling computation, a two-element microstrip array is treated as a two-port network with a 2×2 port impedance matrix. With the surface current densities on the two patches solved, the mutual coupling coefficient can be evaluated from

$$S_{12} = 2Z_{21} \cdot Z_0 / [(Z_{11} + Z_0)^2 - Z_{21}{}^2], \quad (1)$$

where Z_0 is selected be 50Ω; Z_{11} is the self-impedance of the excited antenna; Z_{21} is the mutual impedance between the two antennas.

As for the cavity-model analysis, the thin-substrate condition is assumed. It is also assumed that the mutual interaction does not disturb the interior field distribution inside the cavity below the microstrip patches. In this case Z_{11} is set to be 50Ω. The impedance Z_{21} between the two patches can be calculated from the interaction of the magnetic field, set up by patch 1 on patch 2, and the equivalent magnetic current of patch 2. With Z_{21} evaluated, S_{12} can be calculated from (1). For the GTLM method, the thin-substrate condition is also assumed, and the microstrip patch is modeled as a transmission line loaded with a wall admittance at the radiation aperture of the patch. By replacing the section of transmission line with an equivalent π network, an equivalent circuit can be derived and Z_{11} can be formulated using simple circuit theory. By further including the mutual admittance between the radiating edges of the two patches into the equivalent circuit, Z_{21} can be derived, and S_{12} can be easily calculated from (1).

Also, radiation patterns of an $N \times N$ microstrip array mounted on a cylindrical body are analyzed using a full-wave approach. Theoretical results are also verified by the experiments. A significant curvature effect on the radiation pattern in the roll plane is observed. The side lobe level is strongly dependent on the cylinder radius, especially for the case of a large array size. On the other hand, the curvature effect on the radiation pattern in the axial direction is small and can be neglected.

Powerful Algebric Tools for the Modeling of Microstrip Antennas Mounted on Arbitrary Conformal Structures

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Conformal microstrip antennas can be mounted over the surface area of a vehicle (aircraft, missile, satellite, etc.), allowing minimum airstream disturbance. The increasing potential use of non-planar microstrip antenna began to appeal to a lot of researchers [1-9]. The study is always a difficult task. The wide diversity of the structures (simple as cylindrical, spherical, conical, and more complicated as ellipsoidal, for example), the complexity of the electromagnetic equations, and the cost of real experiment plead in favor of new kinds of simulations.

We propose an original powerful algebraic tool based on fast and accurate symbolic algorithms for the analysis and design of the microstrip antennas mounted on arbitrary conformal structure with the help of a Computer Algebra System (Maple V). With our symbolic objects the integrability of our model into a CAD package is easy.

In this paper we present original theoretical results for ellipsoid structures from which it is possible to treat other very complicated surfaces. The goodness of the method is validate comparing the obtained results with experiments and those reported in literature. Our modeling is based on a cavity model, and a new concept of the dynamic permittivity. All the expressions of the electric characteristics are given as a polynomial expression of the geometrical and physical parameters so that the electric characteristics of the antenna can be fast evaluated [8-9].

The expression of the resonance frequency depends on the dynamic permittivity ε_{dyn}, that takes into account either the physical and the geometrical characteristics of the structure, either the fringing effects, and depends on the effective permittivity ε_{eff}; using a variational method taking into account the stacked dielectric substrates by means of the scalar Green's function. The zeros k_{mn} of the characteristic equation, are obtained and reduced to a polynomial form versus the geometrical parameters of the structure.

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A Method for Designing Broadband Microstrip Antennas in Multilayered Planar Structures

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I. Introduction

A microstrip antenna possesses many advantages such as its low profile, light weight, small volume and mass production. The analysis and design of various shaped microstrip antennas mounted on different structures have been extensively reviewed in a book by Pozar and Schaubert [1]. However, the narrow bandwidth of the antennas is the major obstacle that restricts its wide applications. In general, the impedance bandwidth of a microstrip antenna is only a few percent, e.g. about 5%. There appears to be a general lack of information that provides a systematic method for wideband design. In this paper, a practical, conceptually simple, very efficient method for designing wideband microstrip antennas is presented. Utilising this design technique, two antennas were designed and fabricated and the results show a bandwidth of about 25.7%.

II. Method for Designing Wideband Microstrip Antenna

The structure of the microstrip antenna proposed in this paper is shown as Fig. 1. The resonant condition is given by :

$$\omega_r C X_L = 1, \qquad (1)$$

where ω_r is the angular frequency, C stands for the capacitance, and X_L is the inductance of the microstrip antenna fed by a coaxial probe[2]-[3]. Considering the effective permittivities of each substrates, we can use the improved transmission line model to calculate the resonant frequencies of the lower and upper patches[4]. Once the resonant frequencies of the lower and upper patches are determined, the bandwidth can be enlarged by considering the centre frequency as the matching frequency given as follows:

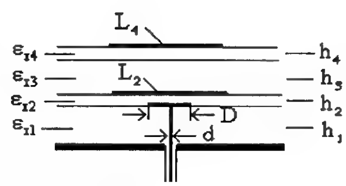

Fig. 1. Profile view of the antenna

$$F_r = (F_{r2} + F_{r4})/2. \qquad (2)$$

Substituting the equation (2) into (1), we can then obtain the diameter D for the given series capacitance[2]-[3]:

$$C = \varepsilon_0 \varepsilon_{r2}[\pi D^2 / 4h_2 + 2D\ln(0.38D/h_2)]. \qquad (3)$$

The capacitance-dependent diameter D can be easily determined by an iterative method from above transcendental equation.

III. Design Results

Two feeding conditions are considered in the design. The antenna parameters have been chosen are: $L_3 = L_4 = 62.5$ mm, $e_{r1} = e_{r3} = 2.2$, $e_{r2} = e_{r4} = 2.6$, and d =1 mm. Fig. 2 and Fig. 3. show the VSWR of the antenna fed by coaxial probe and capacitance plate respectively. The bandwidth of the latter antenna has been enhanced to 25.7%.

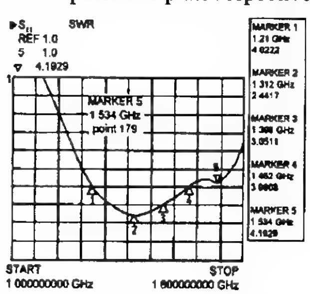

Fig. 2. Coaxial probe feed directly

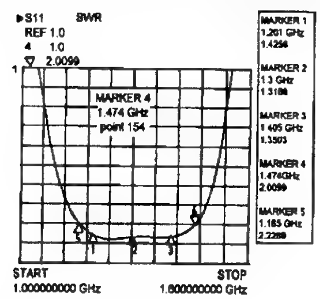

Fig. 3. Capacitance-plate feed

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Analysis of Microscrip Antennas on Spherical Dielectric Substrates Perpendicular to a Ground Plane

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Antennas printed on planar dielectric substrate perpendicular to a ground plane have been used as an infinite phased array [1-2]. As the circuits such as phase shifter can be fabricated on another substrate behind the ground plane, diferent dielectric constant substrate can be used for the circuits and the printed antennas to reduce the size of the circuits and increase the bandwidth of the antenns. Futhermore, the circuits are isolated from the radiating elements. However, the scan angle is relatively narrow because the radiating elements are perpendicular to the ground plane.

In this paper, an antenna printed on spherical dielectric substrate perpendicular to a ground plane is considered. The use of non-planar dielectric substrate for the radiating element provides more design freedom such as tilting of radiating elements. The antenna is excited by a voltage source between the antenna patch and the ground plane. To simplify the analysis, an infinite extended ground plane is assumed and then image method can be applied to replace the ground plane by the image of the microstrip antenna. The radiation pattern and input impedance are determined by the method of moments [3] and surface electric current [4]. The Green's function for a surface electric current on asherical dielectric substrate is used.

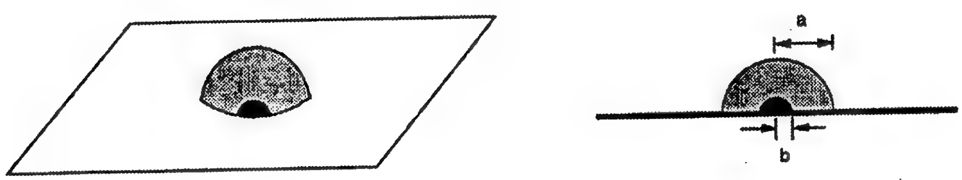

Fig. 1 A microstrip antenna on spherical dielectric substrate perpendicular to a ground plane.

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Session G10
Thursday, July 16, AM 08:40-11:00
Room M
Optical Interconnections in Electronic Systems : Design and Realization (I)

Organiser : E. Griese
Chair : E. Griese

Intelligent Optical Networks

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Optical technologies have the potential to support thousands of high bandwidth optical channels to/from a single CMOS integrated circuit, and can thus allow for the construction of novel bandwidth-intensive computing architectures which are no longer constrained by conventional electronic wiring limitations. In this talk, the architecture of a terabit "*Intelligent Optical Interconnect*" is described. Architecturally, the interconnect consists of a large number of parallel optical broadcast channels, each with several Gigabits of bandwidth. Using current optoelectronic technology, each channel typically consists of 32 parallel optical bits, clocked at 500 Mhz, with a channel bandwidth of 16 Ghz. Using current technology, a typical intelligent optical interconnect may contain hundreds of such channels and support a bandwidth in excess of 1 Terabit/sec. The architecture scales smoothly to wider channels, higher clock rates, and larger aggregate bandwidths, thereby exploiting the "*bandwidth advantage*" of optics. Unlike "*Passive Optical Networks*", the proposed optical interconnect is "intelligent" and can implement the communication primitives used in computing and telecommunication systems directly in the CMOS optoelectronic integrated circuits, which act as the interfaces between the electrical and optical domains. Such primitives include switching, broadcasting, multicasting, error and flow control, filtering, packet buffering, and synchronization. The Intelligent Optical Interconnect architecture is manufacturable using existing batch fabricatable CMOS optoelectronic integrated circuits. Several optoelectronic integrated circuits, consisting of optical I/O merged with CMOS substrates for data processing, will be shown. An experimental system demonstrating these concepts, in the form of a terabit "*Intelligent Optical Backplane*", is under development in Canada.

Optical Interconnection Subsystem in Parallel Processing Machine RWC-1

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A Gbyte/s-class optical interconnection subsystem for a parallel computer was developed and it operated stably in the testbed system of a parallel processing machine RWC-1 (Real World Computer-1). Although it consisted of MMF parallel optical modules, data was transmitted over 1 km because of the deskew operation of a one-chip transmitter and receiver LSI. Random packets were transmitted without error over 17.5 hours, corresponding to a BER of 10^{-15}.

Optical interconnections are in high demand for connecting nodes of parallel processors because high-speed and high-capacity electric interconnection has difficult problems such as a short connection distance, EMI, large volume, heavy weight, too many signal numbers, etc. We have developed a system-designer-friendly optical interconnection subsystem by adding a one-chip data-link LSI to optical modules which makes the interconnection stable and calibration-free. Also, MMF array optical modules realize high-capacity but compact and low-cost interconnections.

Functional blocks of the optical interconnection subsystem are shown in Fig. 1. The 8b10b codec makes the subsystem transparent to data-format including de (continuaous "0" or "1"). Mux/demux decreases the data width from 48 to 6. Array E/O and O/E modules have 8 x 1.1 Gbps capacity with very small volume of 17.6 cc. Fig. 2 shows the optical interconnection subsystem mounted on a single board. It has an array transmitter and receiver module with one-chip data-link LSI per channel. Fig. 3 shows th edeskew operation. The fiber length of channel 6 was 1 meter longer than those of the other channels. This caused a 5-nm delay, as shown in left-side waveform of Fig. 3. The skew was completely compensated in the receiver LSI and the 48 bit parallel data synchronous to the PE clock was reformed .

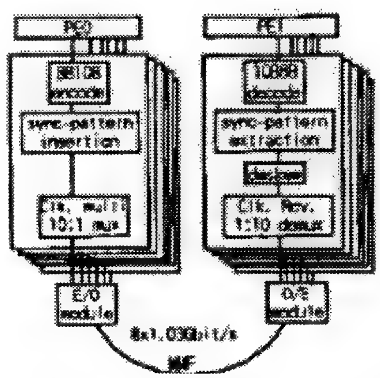

Fig.1 Functional Block of the optical interconnection subsystem

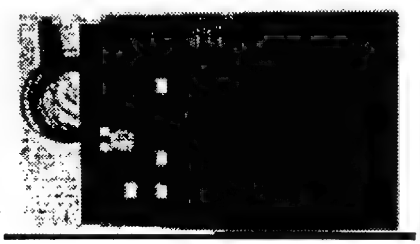

Fig.2 Optical interconnection subsystem mounted on a single board

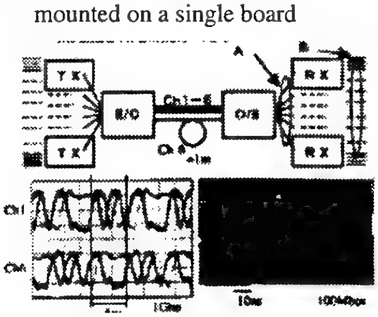

Fig.3 Deskew operation. 5 ns-skew was intensionally added to ch.6 (left side waveform at A) and commensated (right side waveform at B

VLSI Processing Using Optoelectronics and Optical Interconnects

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Limited bandwidth is one of the major hurdles in the effort for more computing performance in today's computing technology. Performance losses arise from bottlenecks in data paths about all distances. This holds for loosely-coupled systems during communication in system-to-system and board-to-board area as well as in tightly-coupled systems in the chip-to-chip communication. Increasing clock rates and the growing transistor density in future microprocessors will enlarge the imbalance between satisfying computing power on the one hand and insufficient communication performance on the other hand. To improve the performance of electronic interconnects imposes severe difficulties due to fundamental physical reasons. In contrast to that using optical interconnects in electronic systems allows to combine the strength of optics in data communication with the strength of microelectronics in data processing.

Recently achieved advances in microoptics and optoelectronic very large scale integrated (OE-VLSI) circuit technology offer the potential to overcome the limitations occurring in pure electronic systems. Fibre arrays, diffractive and refractive microoptic components used as deflection modules can serve as 2-dimensional optical input/output (I/O) interfaces for OE-VLSI circuits. Such systems will have much more interconnection density than pure electronic systems and do not suffer from performance losses arising by too slow and too few external pins. Parallel optoelectronic computing systems consisting of such optical interconnection modules and OE-VLSI circuits can be mounted on glass substrates which work as optical motherboards and optical multi-chip modules.

In the talk we present first results we gained in experiments and simulations on different OE-VLSI circuits. These circuits were designed for various architectures like binary neural associative memories, fine-grain superscalar 3-D integer processor cores and reconfigurable optoelectronic digital signal processors. For the realisation of the OE-VLSI circuits we investigated different alternatives. One alternative concerns smart detectors consisting of CMOS circuitry monolithically integrated with a silicon based array of photo diodes. Furthermore we designed an OE-VLSI chip based on quantum well diode arrays. Such an array operates as a parallel optical I/O interface which is hybridly mounted with flip-chip bonding technique on top of a CMOS circuit. We will compare and evaluate these technologies as well as the possibilities to connect them by optical means.

Design of a Free-Space Photonic Backplane

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Over the past few years a great deal of interest in the field of free-space photonic backplanes has been shown by academia and industry. This work has been primarily motivated by the limitations of conventional electrical backplane technology. In addition, advances in the field of free-space optics, including the develoment of hybrid CMOS/SEED devices, vertical cavity semiconductor lasers, low cost diffractive optics, and architectures capable of taking full advantage of the massive parallelism of optical links have made the developent of a commercial system feasible.

In this paper the design of a prototype free-space four-stage photonic backplane will be described. The system uses CMOS/SEED modulatour based smart pixels to interface between the printed circuit boards and the optical backplane. Microchannel relays and polarization optics are used to direct the optical data between the various stages in the backplane. The optics employ a clustered window configuration in which multiple signal beams are relayed via each microchannel. This approach has advantages in terms of the systems scaleability and alignment tolerances. A total of 256 optical data channels per stage, each running at 100's Mbits/sec could be used to relay data between stages. This gives the backplane an aggregate throughput of >100Gbits which exceeds current electrical backplane performance.

The optical layout, optomechanical design, and alignment tolerances of this backplane will be discussed. In addition, the potential for scaling this technology for commercial applications will be described. The author would like to acknowledge the Canadian Institute of Telecommunications and the Nortel/INSERC IRC in photonic systems.

An Overview of Polymer Fiber Optical Interconnect Program at NEC Research Institute

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Polymer fibers as cost-effective interconnect solutions have recently drawn increasing attention. Potentially low material, fabrication and connection costs are the main reasons of using polymer fibers for short distance inter-board and inter-computer bandwidth-demanding networking applications. In this talk, we review recent R&D progress made at NEC Research Institute in areas of polymer fiber based optical interconnects. In particular, research efforts in the following four areas will be described:

(1) Side-coupling using large-core polymer fibers;
(2) Modular & planar star-coupling using large-core polymer fibers;
(3) Bit-parallel 2D data links using polymer image guides, and
(4) Optical clock delivery using embedded thin polymer fiber bundles.

Conventional Printed Circuit Boards with Integrated Optical Interconnects

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Microprocessors of the next or the next but one generation will have at least 64-bit architectures and on-chip clock frequencies in the range of 1Ghz. This performance can solely be totally used if the communication channels between different components perform a corresponding bandwidth. The performance of conventional electrical interconnects are limited due to dispersion, emission of and susceptibility against electromagnetic radiation. To overcome these problems and disadvantages optical interconnects can be used in order to perform communication channels within systems having a very high bandwidth on the one hand and being almost completely insensible to electromagnetic noise on the other hand.

In this paper we propose the integration of optical interconnects into conventional multilayer printed circuit boards by adding a passive optical layer. This solution combines the advantages of microelectronics and optics and the disadvantages of both technologies can be avoided. The special optical layer which has to be an inner one with regard to thermal and space constraints, contains the different optical wave guides. In order to be as compatible as possible with the existing manufacturing process of printed circuits boards the cross section dimension of the wave guides will be in the range of 100 μm, which means that for this application multi-mode technology will be used. Furthermore, the growing VCSEL technology will be able to perform cheap and robust optical drivers with a very narrow beam which allows their connection to the waveguide without expensive micro-optical components, like lenses.

Concepts, necessary design rules and algorithms as well as first results in designing and realizing this kind of hybrid systems will be discussed and presented. Furthermore, practical solutions for the optical drivers and detectors are introduced.

Session G11
Thursday, July 16, AM 11:00-13:20
Room M
Photonic Crystals : from Microwave to Optics
Organiser : J-M. Lourtioz, E. Yablonovitch
Chairs : J-M. Lourtioz, E. R. Brown

First part :

3D Metallo-Dielectric Photonic Crystals with Strongly Capacitively Coupled Metallic Islands

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Los Angeles, CA, 90095-1594

We introduce a new type of metallo-dielectric photonic bandgap structure, intentionally incorporating very strong capacitive interactions between the periodic metallic islands. The bandgaps become huge, with the "valence band edge frequency being pushed down by the capacitance between metallic islands, while the "conduction band edge" frequency continues to depend on lattice constant as in normal PBG's.

Localization in Metal PBG's at Millimeter Wavelengths : Finite Superlattices and Microresonators

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Localization effects in finite metallic photonic band gap are investigated by means of scattering parameters measurements and electromagnetic simulations at millimeter wavelengths. The fact that the periodic structures have finite dimensions influences drastically not only the dispersion characteristics but also the diffraction properties. With respect to the former issue, a clear analogy with the envelop wave function approach, extensively used for semiconductor superlattices, is found opening the way for photonic band gap engineering. For diffraction related phenomena, several scattering modes are pointed out with notably scattering processes which can be compared to those involved in a Pachinko game. On the other hand by introducing local perturbations within the crystal lattice, high Q micro-resonators can be fabricated whose electromagnetic characteristics can be accurately predicted from the electromagnetic field quasi bound eigenstates. Potential application in terms of guiding, filtering and radiating elements are discussed in a last stage.

Issues in the Control of Guided Waves by Two-Dimensional Photonic Bandgaps for Optoelectronics

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The implementation of two-dimensional photonic bandgap periodic microstructures in optoelectronics could be a key-factor to improve the lateral control of light in the many guiding heterostructures that are at the heart of emitters, modulators, detectors, and in other integrated-optics devices. Whereas the interaction of plane waves with a two-dimensional photonic crystal is now well documented, it is not the case for the interaction of guided waves with a periodic array of air holes, even in the case where these holes are infinitely deep and the guide is well buried (Fig.1). An important progress was the original idea of T.F. Krauss [1] that a reduced air-filling factor of the holes avoids scattering outside the guide and is thus central to obtain a PBG behavior from guided waves, albeit without absolute gaps. This idea led recently to some successes that we will review, both in their one- and two-dimensional versions. Experimentally, we will discuss how the challenge of measuring transmitted, reflected and in-plane diffracted waves from a single deep-etched PBG pattern can be tackled [2] and how the results answer to the simple question : where does light go ? We will also discuss what can be deduced from the quality factor of a cavity between two similar patterns .

Still, considering the geometry of interest with a planar dielectric waveguide traversed by infinite air holes (Fig.1), it would be very desirable to know its physical limits. In particular, it is crucial to know whether a moderately low index substrate may suffice (e.g. AlAs) or if a still lower index (e.g. Alumina of 'Alox') is needed to improve device performances. A numerical study complementary of existing approaches (Ref. [3] in particular), would therefore be extremely welcome. We will try to give a hint along this road.

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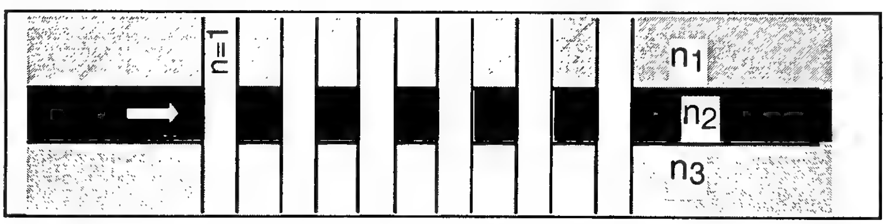

Fig.1 : Guided waves impinging on a periodic array of infinitely high air holes. The guide indices are n_1 for the core, with the largest index, n_2 (upper clad) and n_3 (lower clad) . It supports a single mode when unetched. Holes have an index n=1.

Photonic Crystals as Optical Fibre Waveguides

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Periodically microstructured materials are a subject of active research because of their unusual and potentially useful optical properties. In this talk we describe a new form of photonic crystal device – a fine silica fibre which is many metres (even kilometres) in length, and which has a fine array of holes running down its length (figure 1). The periodic structure is formed on a macroscopic scale as a fibre preform: the transverse dimensions are then reduced by drawing it down on a fibre-drawing tower. The resulting silica/air photonic crystal has a pitch of the same order of magnitude as an optical wavelength, giving it optical properties which differ substantially from those of conventional bulk materials [1], [2].

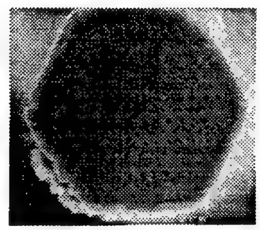

Figure 1 :

SEM micrograph of the cross section of a photonic crystal fibre waveguide. The air holes of diameter 250nm are spaced by 2.2 μm. The solid region in the centre forms the fibre core.

By introducing a defect site into the crystal structure one can create localised optical modes, so that the photonic crystal fibre acts as a low-loss waveguide. Such modes fall into two distinct classes: those which are guided by «Bragg» reflection, and those which are guided by using the photonic crystal as an «effective index» medium. The first type of guided mode is formed when a two-dimensional photonic band gap in the periodic medium is used to confine the light to a defect location [3]. This could be a low-index defect (e.g. a large air hole) and the guided mode can have a propagation constant which differs substantially from those found in conventional waveguides. In the second type of waveguide a region of effectively higher refractive index is formed in the fibre – for example by removing a single air hole from the structure. The modes thus formed display some remarkable and counter-intuitive properties resulting from the complex interaction between the guided mode and the periodic cladding region [4,5]. These two types of waveguides have many potential applications in developing both passive and active devices.

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[5] J.C. Knight, T.A. Birks, P.St.J. Russell and J.-P. de Sandro, «Properties of photonic crystal fibre and the effective index model,» to be published in JOSA A.

Light-Commandable Defects in a Three-Dimensional TeraHertz Photonic Crystal

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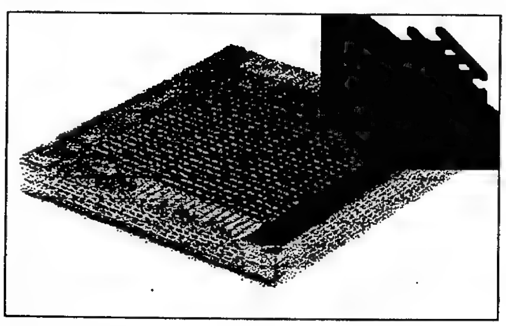
The increasing interest brought to sub-millimetre photonic band gap crystals comes from their potential use as efficient antenna substrates, filters, wave-guides, etc. We report the fabrication of a sub-millimetre three dimensional photonic crystal by a new, simple, low cost and material independent mechanical machining technique. Silicon wafers are mechanically machined with a dicing saw and stacked together to obtain a three-dimensional photonic crystal (wood-pile structure). The defects were created by inserting silicon cubes in interstitial positions inside the crystal.

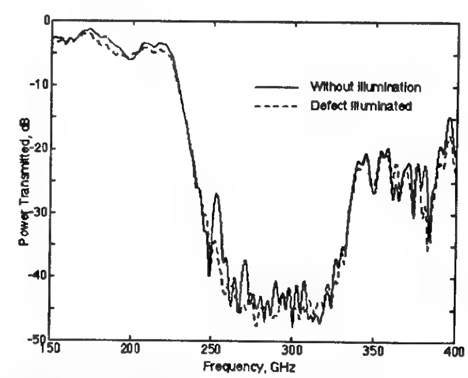
We used a terahertz time-domain spectroscopy setup to measure the transmission of the photonic crystal for different directions and polarisations, as well as its refractive index.

Systematic measurements of the photonic band gap parameters in function of the number of layers were performed. The crystals showed high transmission for the frequencies lower than the first band gap and a 45 dB attenuation, reaching the measurement limits, in the forbidden gap and this for only 6 periods of crystal. A wide complete photonic band gap, centered at 265 GHz with a 19% band-gap to mid-gap frequency ratio, and excellent filtering properties (2.2 dB/GHz slope at 240 GHz), were observed as well as Fabry-Perot type oscillations and second order band gaps.

The presence of the defects generated transmission modes inside the bandgap. For the first time, we were able to command the transmission coefficient of these defect modes by illuminating the silicon defects with a 300 mW laser beam. A 8 dB transmission modulation was obtained for the defect mode at 253 GHz without other changes in the photonic crystal transmission.



Photograph of the wood-pile structure fabricated



Transmission spectra of the crystal with defects, measured with and without illumination

Session H06
Thursday, July 16, AM 8:40-10:00
Room R02
Chiral Media
Workshop on Complex Media and Measurement Techniques
Chair : S. Tretyakov

Spatially Dispersive Media as Physically Realisable Alternatives for the Perfectly Matched Layer

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Perfectly matched layers suggested for the grid termination in FDTD numerical simulations are active media, thus physically non-realisable as composite materials with passive inclusions. In this paper we show that spatially dispersive passive media can be in principle used instead of the active PML. In that case, ideal matching can be achieved with physically-realisable material parameters for the normal incidence on the interface. To achieve uniform absorption effectiveness at oblique incidence angles, the use of higher-order spatial dispersion effects is suggested. With more material parameters available, less severe restrictions apply to the permittivities and permeabilities of the material.

In most cases the authors try to develop PML formulations which would be most suitable for the use in numerical techniques. In that cases such things as field scaling, co-ordinate stretching or complex co-ordinates are quite possible and even convenient. However, if one thinks about physical realisation of media with such interesting properties, one should stick to the cases when electromagnetic fields are governed by the usual Maxwell equations. Properties of the medium should be described by appropriate constitutive relations. Anisotropic medium formulation of the PML is suitable in the sense that in this case PML is "realised" as a uniaxial magneto-dielectric with certain (to be discussed later) material parameters. Unfortunately, this uniaxial material happens to be always active, and thus non-realisable as a composite with passive inclusions.

The purpose of this paper is to consider if and how materials whose behaviour is similar to that of the PML can be possibly realised as passive composite materials. As we shall see, spatially dispersive uniaxial composites (similar to uniaxial omega composites) are potential candidates for that.

Light Reflection from an Anisotropic Magneto-Optical Medium with Arbitrary Direction of the Magnetization

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Three basic configurations are usually distinguished in calculations of the light propagation in magneto-optical media: polar, longitudinal and transverse direction of the magnetization. In the polar and longitudinal cases the fourth order equations for normal components of their wave vectors reduce to biquadratic ones. In the transversal situation we will obtain two quadratic relations. Analytic solution of the equation is obtained also for magnetization in the plane of interface (mixture of longitudinal and transverse geometry). This configuration is discussed in details. If the magnetization is in general direction, the fourth-order characteristic equation should be solved by using numerical methods.

Permitivity tensor is considered for the case of cubic magneto-optical crystal. Its linear and quadratic terms in magnetization are included. Magneto-optical medium is described by the index of reflection and by linear and quadratic magneto-optical constants. In linear approximation the polar and longitudinal magnetization components cause the conversion between s and p polarized modes (magneto-optical rotation and ellipticity) and the transverse magnetization component realizes the change of p polarized (TM) waves. The effects are proportional to the magnetization components. Careful separation of the components is important for the magnetization behavior study by magneto-optical effects.

The second order (quadratic) terms of the bulk conversion reflection coefficients and ellipsometric angles are derived for in-plane magnetization geometry. The second order Kerr rotation and ellipticity are proportional to the product of the longitudinal and transverse magnetization components. The results are demonstrated for Fe layers. The magnetization component influences in general direction are studied by numeric calculation of the reflection coefficients. The mixture of the longitudinal and polar magneto-optical effects is analyzed taking into account the second order terms. The effects of the magnetization components are specified at normal incidence geometry. In this case the calculation becomes simpler.

Alternative Analysis on Bianisotropic Mixtures

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The problem of wave propagation in a random medium where discrete scatterers are randomly distributed has been attracted continuous attention due to its interesting theoretical and practical importance in remote sensing and material science. In the past decades, the distribution of particles is assumed to be periodic or random and the froquet's theorem or multiple scattering theory has been applied to the periodic and random distribution respectively. However, it is also possible that the distribution of particles can change from total uniformity to complete randomness.

An approach, which is applicable to the transition case from periodic to random distribution, has been presented by one of us [Radio Sci.,22,881(1987),IEICE Trans. Electron.76-C,1357(1995)]. This approach can handle the case where the scatterers are dislocated randomly from a periodic distribution.

In this paper, we assume that the mixtures consist of an isotropic background medium in which bianisotropic, spherical inclusions are embedded. The microstructure of bianisotropic mixtures is random dislocation from a periodic distribution. That is, the distribution of bianisotropic particles is identical to that of dielectric particles given in our previous papers and different from that of bianisotropic particles assumed in current literature. Following Tateiba's method, we approximately transfer the medium parameters of the original mixture with random dislocation from a periodic distribution as those of the other mixture, the background medium of which is a continuous bianisotropic medium ,the scatterer number density of which is the same as that of the original mixture. But each inclusion in the transformed mixture is greatly changed. Actually, the static polarization of a transformed scatterer can be discribed as the polarization difference of two homogeneous bianisotropic spheres. Numerical results of the effective medium parameters of anisotropic mixtures are presented.

Numerical Solution of Scattering Problems Due to Three-Dimensional Chiral Bodies by Using the MoM/FEM Hybrid Method

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Introduction - In this contribution, we present the application of the hybrid Moment/Finite Element Method (MoM/FEM) [1] for the solution of electromagnetic scattering problems due to inhomogeneous chiral bodies. The relevance of this topic is clear because of the growing interest in the use of the chiral materials in the control of absorption, scattering, and shielding for various real configurations, which cannot be modeled by means of simple geometries. The MoM/FEM method which has been proved to be a very powerful tool in the solution of scattering problems related to inhomogeneous media with finite extent, seems to be able to predict e.m. field distributions scattered by chiral bodies in a very efficient way.

Method - The surface equivalence principle is used to replace the chiral scatterer by equivalent surface currents. These currents radiating in the unbounded external medium, produce the correct scattered field outside. When radiating in the bounded chiral medium, they produce the correct total internal field. By enforcing the continuity of the tangential components of the total electric and magnetic field on the surface of the object, a set of coupled integro-differential equations is obtained for the equivalent surface currents. The interior problem involving the chiral medium, is solved by the Finite Element Method, and the exterior problem dealing with the unbounded region is solved by the Moment Method. In more detail, the coupled operator equations, resulting by the application of boundary conditions on the surface of the chiral scatterer, are subsequently transformed into matrix equations using the moment method. Successively, the matrix terms related to the electric field in the interior region, are obtained by the finite element method.

Results - To validate the method, numerical results, including echo-widths and internal field distributions, for the scattering by three-dimensional chiral objects are presented and compared with available data (analytical solutions when possible or approximate solutions obtained by using other numerical methods [2]). On the other hand, to illustrate the features of the application of the MoM/FEM method to the scattering by chiral objects, numerical examples are presented and discussed in more details to show the capabilities and the efficiency of the proposed approach.

Rerences

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J. I. P. R. 4 - Session I08
Thursday, July 16, AM 08:40-12:20
Room 200
Polarimetric Signal Processing

Organisers : G. Wanielik and E. Pottier
Chairs : G. Wanielik and E. Hanle

Near Grazing Angle Measurements of Terrain and Vegetation at 76 GHz

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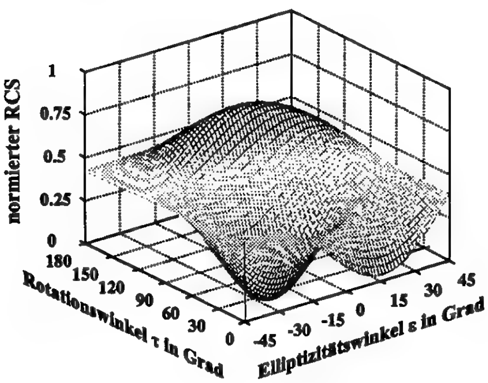
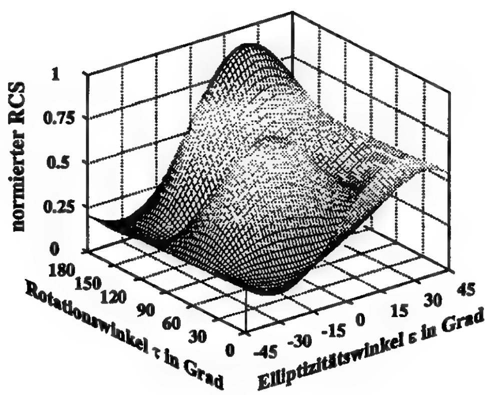
The polarimetric signature of an electromagnetic wave scattered from terrain and vegetation at near grazing angles is investigated. The study makes use of a monostatic, fully polarimetric millimeter wave measurement system working at 76 GHz as well as at 140 GHz. A comparative study of the polarimetric measurement data obtained at these two frequencies is presented, specially focusing on the differentiation potential of polarimetric measurements at any of these two frequencies for terrain and vegetation that is found in urban environment.



Co-polar response of a gravel surface for 140 GHz at an incident angle of 5 degree



Cross-polar response of a gravel surface for 140 GHz at an incident angle of 5 degree

Estimation cof Invariant Jones Matrix Parameters of the Tropospheric Radio-Propagation Channel

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The TUCSR, Radio Engineering Department developed over the past four decades, the Kolarovo Wave Scattering and Propagation Laboratory on top of the 'Blue Cliff', overlooking the tom river (8 km SE from the TUSCR Electronics Engineering Campus), for conducting atmospheric and tropospheric polarimetric wave scattering and propagation path measurements. In this presentation recent results on bistatic polarimetric radar measurements of the Jones propagation matrix are presented and discussed. It is shown that the estimates of the modules of the eigenvalues and phase parameters of the Jones matrix can be recovered in real-time from non-coherent bistatic measurements. Practical applications of the presented method may be implemented for recovering the polarimetric information on the radiophysical properties of tropospheric radio wave propagation channels in the VHF and UHF bands.

Modulation Technique and Data Acquisition in a Multifunctional Polarimetric Near Range Radar Sensor

U. Siart[1] and J. Detlefsen[1], M. Wollitzer[2], G. Wanielik[2], A. Schreck[2] and J. Buchler[2]

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Future automobile generations need low-cost sensors which provides as much of the desired parameters as possible. We designed a highly integrated mm-wave radar sensor and an experimental setup to evaluate its performance. It is designed to measure important parameters of automobile driving dynamics and boundary conditions for example velocity, pitch angle, distance to ground and condition of the road surface. To achieve these capabilities, a new combination of a dual frequency CW mode and a polarimetric mode is used.

The coherent system consists of two bistatically oriented microwave frontends with five receiving channels altogether. There are two orthogonal polarization channels in each module and one additional reference channel. The dual frequency CW technique enables measuring the distance and the Doppler shift while measuring the polarimetric scattering matrix lets us classify the road surface.

Active control systems like intelligent break control, illumination control or advanced security systems require fast update rates of the controlled variables. Thus the data acquisition sequence consists of 20 ms long data bursts. In addition, this allows a synchronized video recording with each data set belonging to its video picture. The adjustment of the sampling rate, e.g. the use of the subsampling technique, keeps the data rate as low as possible. The double-conversion-superheterodyne concept allows us to realize the dual frequency CW mode with two fixed tuned sources, although frequency stepping is done in time sequence. This decreases transient responses due to frequency-shifted oscillators. The two sources act as transmitter and LO by turns. Thus we don not need an addition LO.

Using the dual frequency CW technique, one can suggest an integrated implementation of the sensor with comparatively uncomplicated signal generation. This facilitates low-cost manufacturing and gives high reliability.

Monostatic Polarimetric R.C.S Near-Field / Far-Field Transformation

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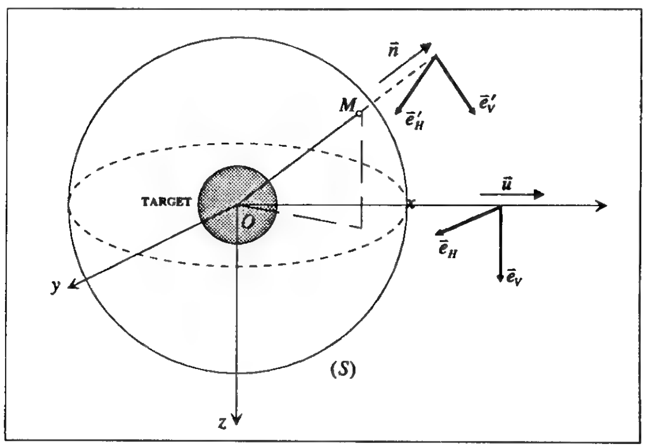
The development of new equipments (planes, ships, satellites, ...) often requires the radar cross section (RCS) of these objects have to be well known under far-field condition in which electromagnetic waves are assumed to be planar. Assuming the distance between the measured object and the probe antenna must be higher than $2D^2/\lambda$, with D the largest dimension of the object and λ the wavelenght, the dimension of some measured objects may be too large to carry out the far-field radar cross section. In order to solve this problem, the RCS of a target can be measured under near-field condition and the far-field RCS is derived from measurements using a near-field/far-field transformation.

In this purpose, we have defined a new theoretical polarimetric method to compute the far-field RCS in the monostatic case. For a polarimetric application, the RCS of a target is characterized by the Jones vector. Then, the proposed method allows the derivation of the Jones vector in far-field area by computation on Jones vectors measured under near-field condition. The geometrical configuration of the method is illustrated on the following figure :



The Jones vector of the target, enclosed in a virtual sphere *(S)* (radius *R*) and located at the centre *O* of this sphere, is measured for several positions $M(\vec{n})$ of the probe antenna over the surface of *(S)*. The near-field Jones vector $\vec{E}_{meas}(\vec{n})$ is then expressed in the polarimetric basis $\{\vec{e}'_H, \vec{e}'_V\}$ associated with the location of the probe. By using Huygens principle, the Jones vector $\vec{E}_{ff}(\vec{u})$ in a far-field direction $\vec{u}$, which polarimetric basis is $\{\vec{e}_H, \vec{e}_V\}$, is derived through the expression :

$$\vec{E}_{ff}(\vec{u}) \approx cste \cdot \iint_{(S)} \left[\left(\vec{n} \wedge \vec{E}_{meas}(\vec{n}) \right) \wedge \vec{u} \right] \cdot \exp\left[j2\beta R (1 - \vec{n} \cdot \vec{u}) \right] dS$$

Polarimetric analysis of Ramses SAR images

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The airborne experimental radar RAMSES, developed by ONERA, is able to currently provide full polarimetric data for several frequency bands (measurements in L and S band can be performed simultaneously). A data base containing full polarimetric SAR images from various areas of different vegetations and man-made objects, for several frequencies and resolutions is being set up. In parallel, an interactive software designed to the analysis of SAR and ISAR polarimetric 2D images is under development. The purpose of the research undertaken is to bring to the fore the cases where the full polarimetry is essential to target discrimination and identification.

A great deal of polarimetric parameters are proposed in the litterature. In fact, they form several sets deduced from the various polarimetric quantities representing the electomagnetic interactions. In the field of the analysis of SAR images, the polarimetric parameters can be splitted into two classes according to the degree of randomness of mechanisms:
- The Polarisation Fork angles and the (deterministic) Mueller matrix parameters. They allow to get some information about the nature of the electromagnetic interactions generating the few scattering centers which generally characterize man-made targets (single targets) : buildings, planes, trucks, railways, roads... These parameters are all the more significant as the image resolution is high. For low resolution SAR images, we have shown that the polarimetric information may be nevertheless significant in some cases .
- Other parameters of statistical type allow the analysis of large areas (distributed targets): forests, fields, urban areas....The scattering mechanisms are generally very complex and must be represented by statistical quantities (which can be averaged). These parameters are derived from the Mueller matrix (having a physical meaning in term of wave interaction) on the one hand and by the covariance and coherence matrices which are statistical quantities on the other hand . Some parameters like entropy and correlation coefficient hh-vv allow to qualify the level of disorder. Others are more connected to the nature of the dominant or mean mechanism (Cloude decomposition). In a general way, it can be concluded that the greater is the disorder and the lesser the identification is possible.

The first results of the analysis of some full polarimetric SAR RAMSES images (taking into account the ground-truth information on vegetation and on man-made objects obtained from a survey on the site) are presented as a function of frequency and resolution.

Tools for Characterizing Antenna Polarization

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In order to establish the polarimetric characteristics of an antenna from the co- and cross-polarized components of the radiated far-field, we have defined and developed three complementary tools in three distinct domains : the *polarization space*, the *radiation space*, and the *source domain*.

The first tool is a mapping of the polarization states onto the orientation (or tilt) and ellipticity angles rectangular plane, which is in fact a two-dimensional cylindrical projection of the Poincaré sphere. This plot is then used to analyze the various radiated polarization states. Histograms on the orientation and ellipticity angles may also be considered to specify the polarization dispersion around the central co-polarized state.

The second tool is a mapping of the antenna polarization onto a two-dimensional projection of the radiation space. The polarization information is displayed using a color code of the orientation-ellipticity plane. Reduced to a single color parameter, the antenna polarization may thus be imaged in any two-dimensional projection of the radiation space defined by two independent components of the wave vector. This tool is then very useful to analyze the antenna polarization distribution in its radiation space, and to determine its effective co-polarization coverage.

The third tool is an imaging technique that realizes the inversion of the radiated far-field over a hemisphere at fixed frequency. The reconstructed image is a two-dimensional transversal *cut* of the antenna along its principal axis (*plane-to-plane* imaging technique). This tool is then used to identify and localize the radiating centers which effectively contribute to the antenna far-field radiation. Polarimetric images may then be introduced to provide information about the polarization of the extracted radiating centers.

To illustrate these three polarimetric tools, the characteristics of a measured parabolic reflector are presented.

Polarimetric Selection of the Targets with Adaptive Signal Processing

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One of ways of improvement of the radar-tracking detection of slow moving targets on background of the scattering from sea and earth surface, weather objects is an application of polarimetric adaptive selection algorithms.

In this paper on the basis of experimental data received with the help of polarimetric 3 cm radar in the linear polarization basis {H, V} the polarimetric selection of different types of the targets has been investigated.

Some methods of the polarization selection using in the processing procedures the components of polarization matrix components [S(hh),S(hv)], [S(vv),S(hv)], [S(vv), S(hh)] were investigated.The analysis has shown: the factor of the polarization selection for anisotropy objects and weather objects had the values about 0.02 - 0.08; for earth and sea surfaces this factor was equal from 0.07 up to 0.43. Isotropy objects had the values of polarimetric correlation factor for hydrometers about 0.7- 0.8, for earth surface about 0.8 -0.9, for sea surface - from 0.33 to 0.7. For real targets the factor of polarimetric correlation had smaller value, than for corner reflector, but larger than for anisotropy objects : from 0.4 to 0.6.

Experimental results are presented in the paper and have shown the following. The greatest possible value of interference suppression calculated on the basis of long-duration average of signals under constant weather conditions, was for [S(vv), S(hh)] about 10 dB, for [S(hh), S(hv)] - from 20 to 40 dB, for [S(vv), S(hv)] - from 10 to 30 dB depending on kind of interference.

The efficiency of adaptive algorithms of anisotropy target's selection on background of the earth and sea surfaces changed from 5 up to 16 dB, and on background of the hydrometers could reach 30 dB.

The presence on spreading surface of the targets with distinguished polarimetric properties destroys spatial uniformity of the background and is a physical basis for adaptive spatial-temporary polarization selection algorithms proposed in the paper. The results of theoretical and experimental investigations of adaptive polarization selection algorithms have shown that procedures of processing based on the direct reference of a correlation matrix provide higher efficiency, than procedures, based on suppression of the interference.

Comparison of Simulation Results of Polarization Parameters' Doppler Modulation with Experimental Data

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Detection of targets moving against background is an important problem in many radar applications. To effectively solve it, an extensive class of coherent radars with different levels of complexity has been developed. However, there are such scenario of radar surveillance (near zero value of the targets' radial velocity component; small reflective ability of moving targets to be detected; etc.) where advantages of the coherent mode become not obvious. Concerning non-coherent real aperture radars, it should be noted that these systems, as a rule, differ from the coherent systems by more simpler design and have a less cost in mass production. In other words, there is a certain "niche" where small-sized non-coherent real aperture radars, capable to detect moving targets, could take their worthy place. Probably, airborne surveillance radars, navigation radars for small displacement boats, battlefield radars and others could form such "niche".

The use of polarization techniques in real non-coherent radar systems has shown that some of the polarization parameters being measured in real-time have a significant sensitivity to movement of targets of interest. The fact of doppler modulation of the polarization parameters, which describe an observable compound object "background + moving target", has been experimentally proved (see, for example, [1]). However, in spite of the fact that available experimental data confirms this modulation to be a rather stable effect, and it is not an unique fact, this phenomenon is justified insufficiently. So, in [2] it was made with respect to only one of the polarization parameters - degree of polarization anisotropy.

The paper purpose is to simulate temporal samples of the polarization parameters, which correspond to the observation case of an extended target moving against background, with using the phenomenological model of local sources. The subsequent comparison of the results obtained with available experimental data of the parameters measured allows to estimate their coincidence degree and then to correct the model parameters. The author believe that this procedure could be useful in theoretical study of the general problem of polarization-coherent properties of extended radar targets. It is supposed that this procedure would help to answer such important questions as :

- What assumptions must be done that a target could be considered as an aggregate of rigidly connected (or independent) scatterers with certain properties ?
- How a target's movement (not smooth and uniform in general) against statistically rough surface (or radar carrier movement) influences a number, location, coherence degree of its local sources ?
- Whether does it possible to explain the doppler effect manifestation in samples of the polarization parameters within framework of the concept known in radar as "pseudo-coherent mode" (when signal scattered by background is considered as a reference signal) ?
- What are statistical properties of signals phase fluctuations, scattered by "target" and "background", which lead to instability or destruction of the doppler modulation effect ?

The results obtained can be used in evaluation of how and in what extent target's movement is represented in behaviour of invariant parameters of the scattering matrix of the compound object "background + extended target". It is very important for the cases when man-made targets are extended objects and cannot be considered as point objects [3]. Also these results give an opportunity to outline a circle of those polarization invariants, which have the most sensitivity to target's movement and randomness to the surveillance conditions changing.

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Session J07
Thursday, July 16, AM 08:40-12:20
Room 450
Polarimetry, Interferometry and their Combination for Vegetation Studies

Organisers : M. Moghaddam
Chairs : M. Moghaddam, R. Treuhaft

"An Introduction to Polarimetric Interferometry"

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In recent papers [1, 2] we have developed a quantitative framework for the analysis of coherent polarimetric interferometric data. In particular we have shown that due to the polarisation dependence of microwave scattering, the quality of a Radar interferogram depends critically on the choice of antenna polarisation. We have also shown how to use this variation to optimise the quality of the interferogram and maximise its coherence. By applying these techniques to SIR-C repeat pass data we have shown that considerable gains may be had by employing a sensor which can measure complete coherent polarimetric information.

In this paper we review the basic structure of this formulation and present results to illustrate the range of potential applications of this new technique.

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A Unified Analysis of Radar Interferometry and Polarimetry for the Estimation of Forest Parameters

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The vertical structure of forests is a key input to ecological models of forest succession, growth, and productivity. Radar interferometry is primarily sensitive to the spatial distribution of scatterers [1] while polarimetry is primarily sensitive to their orientation [2,3]. In forests, there are obvious correlations between the spatial distribution of scatterers and their orientation. For example, the largely horizontally-oriented ground surface is at the lowest spatial point in a forest and the more randomly-oriented volume is usually at the top and middle. The dominance of either of these features in the radar backscatter will simultaneously produce signatures in both interferometry and polarimetry. For example, for pure volume scattering, an increase in tree height leads to an decrease in interferometric amplitude and an increase in interferometric phase over the bare-surface signatures. If a ground reflection or ground-volume return contributes even at the 10% level to the received signal, the effect on the correlation amplitude can be of the same order and the effect on the phase can correspond to 5-10 meters of topography. This paper exploits these signatures to simultaneously invert interferometric and polarimetric data from the Boreas Southern Test Site for tree height, surface topography, and other parameters as noted below. The data include TOPSAR interferometry at VVVV, where the first "VV" indicates the transmit-receive configuration at the 1-end of the baseline and the second "VV" indicates the transmit-receive configuration at the 2-end; the interferometric data were acquired at two baselines, 2.5- and 5-m. The polarimetry data include HHHH, VVVV, and HVHV powers, and the complex HHVV cross-correlation (amplitude and phase), where the first two letters indicate the transmit receive configuration of the first member of the polarimetric (baseline=0) cross-correlation and the second two letters indicate the transmit-receive configuration of the second member of the cross-correlation.

A simple forward model, a polarimetric generalization of the approach in [1], describes the interferometric and polarimetric cross-correlations in terms of parameters describing the vegetation and underlying surface. The model assumes a flat ground surface under a largely randomly oriented, statistically homogeneous vegetation. The parameters needed to describe the interferometry and polarimetry include tree height, underlying topography, extinction coefficient, ground dielectric constant (real and imaginary parts), and a parameter describing the ratio of the specular to backscattering characteristics of the volume scatterers. Results for tree height and underlying topography will be compared to ground truth. The correspondence will be made between this approach and fully polarimetric interferometry, in which arbitrary transmit-receive polarization combinations are available [4].

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High Resolution Single-Pass Interferometric Radar Observation of Tropical Rain Forest Trees

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High resolution SAR can be operationally attractive for monitoring tropical forest in areas with persistent cloud cover. The purpose of our study is to assess the capabilities of airborne SAR for forest management and inventory. During the INDonesian Radar EXperiment in 1996 (INDREX-96) the Dornier SAR was flown over test sites in Sumatra and East-Kalimantan. This paper analyses two modes for the Sumatra test site: C-band 3 meter resolution, polarimetric; and C-band 1.5 meter resolution, interferometric. The two modes are studied separate and in combination.

Knowledge of forest structure - crown spatial distribution and crown size - and tree species are important for forest management. The interferometric phase difference at C-band is sensitive to relative height differences of leaves and branches in the upper forest canopy. In addition, polarimetric observations at C-band may be useful for individual tree recognition.

Recently, we have simulated the SAR total power and interferometric phase difference for individual trees. Future research will focus on :

- simulation for a forest scene;
- model validation and calibration based on ground data and aerial photography;
- formulation of inverse methods for reconstructing the position of the upper forest canopy;
- formulation of forest information retrieval algorithms.

Of special interest is the detection of emergent trees. The spatial distribution of emergent trees can be indicative for a certain forest type or soil type.

Multidate ERS Tandem Data Acquired over Hilly Forested terrain : Discrimination of Land-Cover and Forest Types

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Recent studies have shown the grest potential of spaceborne SAR repeat-pass intrferometry for land-cover classification. Using interferometric correlation , it has been demonstrated that forest can be discriminated from other land categories much easily than using classical backscatter intensity images. However, it is necessary to futher study the interest of such date in various conditions like hill terrain, and the possibilities ro separate themes within the forest class. Moreover, the coherence is mainly sensitive to geometrical changes (soil+vegetation) which depend on both acquisition time intrval and season. Short timeinterval offered by ERS Tandem acquisitions appears as a solution to improve the forest classification, whereas seasonal effects are not well understood and must be accounted for.

We analysed four ERS tandem pairs acquired during 95 and 96 on a test site located in the *Lozère département*, South France. This site, which covers 50 by 80 km, presents a great interest because of the variability in forest types and topographic conditions encountered. Most forest stands of various species are homogeneous and even-aged. We used a digital forest inventory (with a 50 meters cell size) characterizing the land cover and forest types in more than 30 types based on spices and structure. Finally, we used a 50 m grid size DEM, allowing to derive sar local incidence angle classes. After having crossed these infromations, we extracted the behaviour of interferometric correlation for the different forest types over hilly terrain.

Forest areas are detected as they show low and intermediate coherence (0.3-0.6), comparing to grasslands or urban areas, which exhibit higer coherence. Futhermore, between the forest themes, a gradient appears as a function of broad forest types and stand density. Deciduous species are less coherent then coniferous ones, but he difference depends on the phenology (leaf-on/leaf-off). Among the coniferous, the more dense stands are, the less coherent they are. However, for the deciduous this effect is less visible. These observations are seasonal dependant and can be explained mainly on the variable ground backscatter contribution showing a greater coherence than vegetation volume scattering. Finally, most covers exhibit a similar behaviour with local incidence angle, that can be partially removed using an empirical correction law.

Following, maximum likelihood classifier was applied on the 4 coherence images and subsets of them, in addition to backscatter change images. Results show that the following classes can be mapped accurately using few dates : spares & dense coniferous, deciduous in addition to water bodies, agricultural fields, grasslands and urban cities which are easily detected. Therefore, coherence images from short repeat-pass interferometry at relevant dates appear to be powerful too classifications.

Modelling Coniferous Forest Backscatter Using Statistically Validated Geometric Information

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Several experimental and theoretical activities have been carried out worldwide to investigate the radar sensitivity to forest biomass and to simulate the scattering due to the various forest elements. Most of the proposed models use a discrete approach, are based on the Radiative Transfer theory and describe the forest medium as an ensemble of discs (leaves) and cylinders (trunks, branches, twigs) over a half-space with rough interface (soil). This approach is also used by the model developed at Tor Vergata University, which combines the contributions of the various scattering sources by a matrix algorithm, thus allowing computation of multiple scattering effects. Some results obtained by that model were shown in IEEE Trans. Geosci. Remote Sensing (1995, pp. 360-371),where the electromagnetic formulation was complete, but the tree geometrical description was based on simple formulas derived by limited data sets; therefore, although some general trends were well represented, the possibility to deeply investigate the effects of forest parameters was limited.

The present work uses the same electromagnetic formulation, but the geometrical parameters, to be used as input data, are derived by statistical relationships resulting from extensive measurements carried out at the Duke forest, dominated by loblolly pine (Kasische etal., IEEE Trans. Geosci. Remote Sensing, 1994, pp. 800-822). We have considered several values of the trunk basal diameter and used the statistical relationships to derive other parameters like number of trunks per unit area, trunk height, number of primary branches per tree, number of secondary branches per primary branch, maximum primary and secondary branch radius, etc. The model has been run considering various values of understory biomass. The backscatter coefficients at P and L band and at HH, HV and VV polarizations have been computed.

The obtained results confirm some general trends which were already observed in the results of the previous simpler approach: P band shows slower saturation effects than L band and HV polarization shows a wider dynamic range than HH and VV polarization. The model results are in reasonable agreement with experimental data shown by Dobson et al.(IEEE Trans. Geosci. Remote Sensing, 1992, pp. 412-415), obtained over Duke and Landes forests. The results of this simulation allow to get an insight into new specific aspects. In particular, by computing the backscatter contributions due to all forest elements we have observed that trunk contribution is higher than branch contribution, or at least comparable with it, even at high biomass. We have also noted that understory produces significant effects, especially in young forests.

Volume Scattering Effects in Radar Interferograms : Foliage and Icy Media

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Interferometric SAR has proven a powerful tool for geophysical studies of the Earth's surface. But certain media, in particular vegetation and ice sheets and glaciers, permit significant penetration of the radar wave into the medium and thus volume scattering effects must be considered. This affects principally the correlation of the observed interferogram. Both foliage and ice exhibit diminished correlation as a result of both volume scattering and random motion of scatterers, but ice in addition shows other decorrelation related to ice flow. Shear flow, either along the surface or within the volume, can cause phase biases as well as decorrelate the echoes. Exploiting these sensitivities permits inference of the internal structure and movement of the ice sheets.

The Representation of Vegetation Scattering Components in Models : Theory and Observation

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A high-resolution, ground-based polarimetric synthetic aperture radar (GB-SAR) has recently been developed at the University of Sheffield. This instrument uses synthetic pulse techniques to obtain images far superior in resolution to those of conventional airborne and spaceborne SARs. These high quality measurements will be exploited to improve the interpretation of SAR imagery and to provide experimental data for validating and developing scattering models.

Recent investigations using GB-SAR have produced a series of vegetation measurements which reveal interesting features relating to polarimetric and multiple reflection phenomena. These results provide an excellent opportunity to test the validity of existing scattering models. The proposed presentation will therefore address the correspondence between the above practical results and those obtained by applying first and second order radiative transfer models.

In the results to be examined, multiple reflection effects have been identified at X-band between leaves having separations of up to 100cm. For these cases, the multiple scattering terms generate a virtual image whose strength is related to leaf separation and inclination. In the geometries examined, direct specular scattering from each leaf was not intercepted by the SAR, but the wide angle scattering from the leaf edges was recorded and corresponding artifacts were observed in the image. High resolution polarimetric images of small leafless ash, sycamore and willow trees have also been obtained and demonstrate the formation of similar virtual images between adjacent branches. These polarimetric results have also identified contributions arising from increased scattering due to nodes where the local diameter of the branch is substantially increased by buds. Furthermore, evidence of high RCS returns is seen at the junctions of branches with the main axis of the tree. In addition, small leaf clusters on the willow tree were observed to give particular polarisation responses which are worthy of investigation.

The manifestations of these features in the resulting images provide ideal data for examining the benefits and shortcomings of currently available scattering models. In particular, all current models make use of idealised descriptions of plant components and their polarimetric response which we are able to examine by direct measurement. We can do this in terms of both the individual components (leaves, branches, etc.) and also the ensemble effect when these occur in the complete tree. We will present precise descriptions of leaf shape and how that affects the RCS, both theoretically and experimentally, and compare it with the idealised versions used in the models. We will also discuss the differences between the microwave image of a tree and how that would be represented in a radiative transfer model. These results and those on multiple scattering will be used to draw conclusions about how they affect the imaging of collections of trees in typical SAR images of woodland.

Model Investigations of the Influence of Tree Distributions on SAR Interferometry of Forests

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Gaps between trees in forest canopies play an important role in the forests' development. The amount of light penetrating the canopy, and hence the trees' growth rate, is strongly dependent on the density of the canopy. Hence in managed forests it is important to perform thinning cutting to ensure maximum production. For forest inventory purposes it is desirable to able to detect and quantify such thinning. The gaps in a forest canopy are also important from an ecological point of view. Whether produced by human influence, or through natural death or damage to the trees, such gaps can provide a more varied environment within the forest. This variation plays a significant role in promoting diversity of species.

In recent years, SAR interferometry has emerged as a promising technique for monitoring forested areas. The phase information obtained can be related directly to the height of the scattering from the forest. In single-pass interferometry the total coherence is also strongly dependent on the vertical distribution of scattering from the forest. Using a number of measurements with different effective baselines it has been shown theoretically that the height distribution of scattering can be retrieved. This is true if the scattering is assumed to be horizontally homogeneous. In the case of non-homogenous canopies a model has been described which takes into account the total area of gaps in the canopy. The results show that in boreal forest the gaps result in an interferometric height which is significantly lower than the true tree height.

In the case of evenly distributed trees (plantations) the assumption of a horizontally homogeneous canopy may be correct. However in less intensively managed forests the trees tend to cluster in groups. In natural forests it has been observed that the distribution of tree positions may be described by a Neyman distribution which includes the propensity of trees to grow in clumps. Clustering of this type results in a scattering distribution which is not horizontally homogeneous. In such cases modelling the gaps by their total area may give erroneous results. This presentation shows how Monte Carlo simulations have been used to investigate the effects of variations in the horizontal distributions of trees within forests on measurements of both interferometric phase and coherence. The scattering from the forest is modelled using the distorted-Born approximation. The results obtained are then compared to existing models where the canopy is assumed to be horizontally homogeneous. Information on the distributions of trees in boreal forests is available from measurements made during a field campaign in southern Finland.

Modeling of Radar Responses of some Land Cover Types for the Interpretation of Polarimetric / Interferometric Measurements

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The phase of SAR responses constitutes a new source of information for applications. Previous studies have shown the usefulness of SAR phase information contained in polarimetric and interferometric data for mapping and for the retrieval of natural surface parameters.

In order to assess the information content of the vegetation, a coherent model has been developed to understand more thoroughly the interaction of the wave with the target medium. The model describes the medium as an ensemble of cylindric and ellipsoidic scatterers which geometry is obtained from ground measurements. The coherent scattered field is computed and the interferometric / polarimetric parameters are derived using a Monte Carlo approach.

This model is applied on several land cover types, such as the pine forest of Les Landes and the agricultural fields of Flevoland, and gives some insights on the behaviour of the experimental radar responses obtained from interferometric ERS data (Les Landes) and from polarimetric and interferometric SIR-C/XSAR measurements (Les Landes and Flevoland). Scattering mechanisms are derived from the model to explain the behaviour of those various target areas.

The combination of polarimetry and interferometry is assessed, based on theoretical simulations and experimental results from the SIR-C/XSAR campaign. Potential applications are derived.

A Hybrid Algorithm for Estimating Forest Parameters from Polsar and Insar Data : an Approach to Minimizing the Need for Ancillary Data

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The ultimate goal of any estimation technique for remote is deriving sufficient number of parameters to describe the targets and their dynamics from remotely sensed data, while supplying minimum ancillary information. Most estimation techniques to date, however, rely heavily on the knowledge of all but a small number of parameters. The reason is the complex nature of the targets on the one hand, resulting in complicated scattering models, and lack of sufficient and descriptive data on the other hand. This work is a step towards circumventing both problems by (1) using simplified parametric scattering models and (2) using an expanded data space comprised of both polarimetric and interferometric SAR data over vegetation canopies. The result is a hybrid algorithm for estimation of canopy height, stem density, and canopy moisture. The only ancillary information needed is the species type. At this stage, only C-band data will be used and only volume scattering will be assumed.

The methodology is as follows: The algorithm consists of two modules. The first module calculates vegetation height from magnitude and phase information of interferometric SAR data given some estimate of the vegetation extinction coefficient (see below). A parametric, analytical model based on scattering principles and statistics of scatterers is used to carry out the calculation. The second module takes the vegetation height derived in the first module, and with the knowledge of species type, builds a representation of the canopy using allometric relationships. Then using polarimetric SAR data (HH, VV, and HV) and parametric models derived by fitting polynomials to a numerical scattering model, dielectric constant (hence moisture) of canopy components and stem density are derived. These estimates are then used to calculate a new extinction coefficient for the canopy, which is used in an iterative fashion with the first module, hence estimating a new canopy height, and so on. POLSAR, INSAR, and ground truth data from BOREAS are used to demonstrate this algorithm. Several stands of varying heights and densities are included and error distributions are reported. Addition of other frquencies and scattering mechanisms will strengthen this algorithm and are planned as future activities.

Session K06
Thursday, July 16, AM 08:40-11:40
Room J
Microwave Propagation in Tropical Regions

Organiser : M. Thurai

Chairs : M. Thurai, P. Watson

The Need for Data in the Tropics for Propagation Predictions

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Radiowave propagation models which are designed to predict effects such as rain attenuation, cloud scintillation or ice depolarisation can only be validated by carefully designed, well maintained and diligently analysed experiments. These experiments need to collect both, radiometeorological in-situ data (like, for example, rainfall rate) and the actual propagation effect (like the attenuation of a beacon signal). To characterise the seasonal and the year-to-year variability of the propagation conditions, such experiments need to run for several years. To characterize the variability of propagation statistics by location, a network of measurement stations is needed.

While long-term measurements are available from locations in the United States, from Europe or the area of the former Eastern Block countries, there are still far insufficient data available from tropical climate regions to arrive at a solid model validation.

Recent efforts of international and regional satellite communications operators and of the ITU have started to alleviate the shortage of data, however, there are still many "white spots" on the map where neither radiometeorological nor propagation data have been collected.

What is needed in the near future are :

- Long term propagation experiments (multiples of one year) with collection of associated meteorological information (rainfall rate, atmospheric profiles)
- Micro-physical observation of the atmosphere using special radar systems, distrometers and cloud base - lidars.

Improved propagation information will allow to utilise the limited spectrum more efficiently and to provide better telecommunications services to countries in the tropical climate region.

Rain Cell Diameter and Heights
A new Model of Rain Attenuation

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It is usually not possible, from measurements on satellite links, to separate the horizontal from the vertical rain distribution. Among the increasing number of tropical experiments, only the one at Lae in Papua New Guinea has, so far, been at a high enough elevation angle, 72.8 degrees, to ensure a relatively simple horizontal rain structure in the slant-path. This has given the opportunity to separate rain height from cell diameter. It was also established that up to a rain-rate of 70mm/Hr propagation was dominated by the presence of just a single rain-cell in the slant-path. Even so, variation in attenuation, sky temperature and rainfall rate were not generally completely co-incident, indicating a highly variable and localised horizontal and vertical distribution of rain. The relative simplicity of single cell activity made it is possible analytically to separate the effects of horizontal and vertical varaitions in rain distribution. From this analysis, based on the concept of an accumulation time factor, first defined by Hannson [1], it was possible to estimate cell diameter, slant path-lenght and height for each rain-rate up to 70mm/Hr. These parameters are then the inputs to a new model of rain attenuation on satellite links. Multiple cells appear in the beam at higher rain-rates because of decreasing cell diameters ; and at lower elevation angles because of the longer projected slant-path. Trough the concept of an equivalent single cell, with an effective diameter producting the same attenuation as the combined multiple cells in the slant-path, a new model has been devised for rain-rates up to 180mm/Hr and elevation angles from 5 to 90 degrees. This model is simpler and compares favourably with the ITU-R model.

Reference

[1] Hannson (1990) : New concept used to predict slant-path rain attenuation statistics, IEE Proceedings, vol. 173, Pt. H., No. 3, pp. 89-93.

Tropical Precipitating Cloud Systems Observed Above Manus Island, PNG, Using Profiling Doppler Radars

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The spatial distribution, depth, intensity, and frequency of occurrence of tropical precipitating cloud systems are important due to diabatic heating which dynamically forces the atmosphere and attenuation of high frequency signals which degrades communication systems. While satellites sample the large spatial scales around the globe (of the order 100 -to- 1.000 km) and surface based scanning radars probe the vertical and spatial structures on smaller regional scales (of the order 1 km), vertically pointing Doppler radars sample the atmosphere directly overhead with a high vertical resolution (of the order 100 meters). The NOAA Aeronomy Laboratory developed, deploys, and maintains VHF, UHF and S-band profiling Doppler radar across the tropical Pacific so as to measure the tropospheric winds and the precipitating cloud systems advecting over the profilers.

Although most of the tropical sites maintained by NOAA Aeronomy Laboratory have one profiler, several sites have two profilers operating at different frequencies. The use of these profiler pairs allows the unambiguous determination of Rayleigh and Bragg scattering within the radar pulse volume. The VHF/UHF profiler pair (6m/33cm)wavelengths) is useful for studying the raindrop size distribution as a function of altitude. The UHF/S-band profiler pair (33cm/10cm wavelengths) is well suited for segregating the turbulent atmospheric air motions from the hydrometeor motions of precipitating cloud systems that may not, due to evaporation through the troposphere, contribute to rain at the surface.

While it is not possible to have two profilers at every site enabling unambiguous hydrometeor detection, a technique based on fuzzy logic has been developed to separate the hydrometeor and clear-air observations when only the UHF profiler observations are available. This technique relies on the statistical distributions of the reflectivity factor, Doppler velocity, and spectral width of the UHF observations? In this presentation, the separation technique was applied to 50 days of observations from Manus Island, Papua New Guinea (PNG), when UHF/s-band profiler pair technique will be then applied to 5 years of UHF observations yielding statistics of precipitating cloud depth, intensity, and frequency of occurrence above Manus island.

Investigation of Rain Fading and Possible Countermeasures on Satellite-Earth Links Operating in Tropical Regions

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One year of observations of attenuation during rainfall are reported from a 12 GHz satellite beacon measurement, associated with the Malaysian Measat broadcasting satellite. Data will be presented in the form of monthly statistics, including simultaneously gathered raingauge data, enabling comparisons to be made with attenuation predicted using a number of published prediction techniques (including the current ITU-R methods). From this aspect of the work, conclusions will be drawn on the validity of current prediction methods in tropical regions operating to satellites at high elevations. Of particular concern is the effective rain height to be used in tropical regions, and also the the point rainfall to path attenuation relationships appropriate to systems operating near zenith.

Further evidence on the modelling of rain attenuation in tropical regions will be drawn from the RAL zenith pointing radar system which has been operated in Papua New Guinea[1] in association with an 11 GHz satellite beacon measurement. Rain height models in stratiform and convective rains deduced from such observations will then be applied to the attenuation data gathered in Malysia. Also the potential contributions from further studies using radars and satellite beacons will be assessed.

Finally, in view of the extreme rainfall climates experienced in tropical regions, the possible use of time-diversity fade countermeasure techniques will be investigated using the Measat beacon data. Here statistics of diversity gain will be presented for the year of measurement. Time diversity techniques are relevant to messaging, retrieval and distribution communications applications, including broadcasting.

References

[1] J. Eastman, M. Thurai, D. Ladd, I. Moore, "A vertically-Pointing Radar to Measure Precipitation Characteristics in the Tropics," *IEEE Transaction on Geoscience and Remote Sensing*, 1995, Vol. 33, No. 6, pp. 1336-1340

Variations of Oceanic Rain Rate Parameters Derived from SSM/I

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About ten years (July 1987- September 1997) of oceanic monthly mean rainfall have been produced using Special Sensor Microwave Imager (SSM/I) data collected on board the Defense Meteorological Satellite Program (DMSP) satellites. The technique, based on Wilheit et al. is improved with the inclusion of a refined land-sea mask, a variable beam-filling correction factor related to the freezing height, and a sea ice filter. Monthly oceanic rain rate parameters (total rainfall, rain intensity, rain frequency, freezing height) are generated at both 5^0 and 2.5^0 latitude/longitude resolutions. The mean rain rate over the 500 latitude bands is 3.0 mm/day, with s.d. of 0.15 mm/day over the ten year period. The sampling error of the monthly means rain rate for the 5 degree product, estimated to be about 38% for a single satellite, shows a dependence on the inverse square root of the number of samples and a weaker dependence on the mean rain rate, whereas the sampling error of the 2.5^0 monthly rain rate shows a dependence of -0.5 to both the sample number and mean rain rate, which is consistent with theoretical considerations. The diurnal, seasonal, and interannual variations of rain rate parameters will be presented. The relation to the Koeppen-Trewartha climate classification scheme commonly used in the prediction of attenuation of microwave and millimeter-wave radio links will be discussed.

Spatial Variation of Rainfall Rate in Singapore

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Analyses of rainfall data collected in Singapore for 1995 and 1996 uncovered significant spatial differences of monthly rainfall rates for five stations. These stations are situated along an East-West line roughly trough the middle of the island. the distances between adjacent stations vary between 5 km and 11 km. Singapore is a small island approximately 42 km form East to West and approximately 23 km from North to south. It is situated at the southern tip of the Malaysian Peninsula 'approximately one degree North of the Equator). The island is fairly flat, the highest hill on the island is only 162 meters above mean sea level. There are hills to the Northwest, approximately 40 km away and to the North, approximately 60 km away in Malaysia (500 to 600 meters a.m.s.l.).

Surprisingly for a small island, there are significant differences of monthly rainfall rates for the five stations. Cumulative rainfall rate distributions for 1995/96 shows that one station may have the highest rainfall rate for one particular month, but for another month, another station would have a highest rainfall rate. This spatial variation of monthly rainfall rate agrees well with monthly isohyet maps of Singapore prepared by the Meteorological Service Singapore (MSS). The results bode well for the possible use of site-diversity operations for earth-space satellite communication systems operating in the Ku-and Ka-bands in Singapore.

Empirical Orthogonal Function (EOF) analyses of daily rainfall pattern over Singapore were carried out for 1985 and 1986 rainfall data by T.K. Lim of the Meteorology Service Singapore ('Empirical Orthogonal Function of the Spatial Patterns of Daily Rainfall in Singapore). Five EOFs representing significant rainfall patterns emerged consistently in the analyses for the two years. One pattern is associated with the Sumatras (squalls blowing in the early mornings from Sumatra) which occur between April and November. Two patterns are associated with the two monsoons, which blow over Singapore. The Northeast monsoon prevails from November to April while the Southwest monsoon prevails from May to August. The other two significant patterns are the inter-monsoon seasons when there are periods of calm or of variable winds, during these periods localized influences from sea breezes normally predominate. the EOF analyses provided a good insight the basic precipitation mechanism.

Modelling of rain Attenuation at a Tropical Location

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Models of rain attenuations are relatively less documented at tropical locations than at temperate climatic locations. Moreover, tropical rains vary widely in space and time. In view of increasing use of millimeter wavelengths for the terrestrial and satellite communications in this region, a reliable rain attenuation model is of utmost necessity. In the present paper, the rain attenuation models are obtained from the drop size distribution (DSD) models of rain in terms of a modified gamma function and a lognormal function. The DSD model in terms of gamma distribution is obtained from the measurements of rain attenuations at an optical wavelength (0.63 micron) and rain rates following the technique of Maitra and Gibbins, 1995 (Radio Sci., vol. 30, pp. 931-941), and the DSD model in terms of lognormal distribution is obtained with the additional measurement of rain attenuations at 94 GHz and following the technique of Maitre et al., 1995 (Proc. 7th URSI Commission F Symp, Ahmedabad, India, November, 1995). The Measurements were carried over a 110 m LOS link operated at Calcutta (23 deg N, 88.5 deg E) which is a tropical location in the ITU-R rain climatic zone N.

The DSD parameters are used to calculate rain attenuations at different frequencies at different rain rates. The power-law relations between the attenuation and the rain rate obtained (A = a*R**b) at different frequencies, for both the distributions. Also, the coefficients 'a' and 'b' are expresses as power-law functions of frequencies.

It is found that up to 70 GHz, the attenuation values obtained from the gamma and lognormal DSD models and from the ITU-R model agree well. Above 70 GHz, the gamma distribution generated attenuations are greater than ITU-R values and the lognormal distribution generated values are less than ITU-R estimates. This is somewhat expected as the gamma distribution overestimates the number of small drops compared to the lognormal distribution.

A Melting Layer Model Investigates Using Doppler Spectra Recorded in Papua New Guinea

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In 1995, the Rutherford Appleton Laboratory developed a vertically-pointing Doppler Radar for studying the propagation characteristics and vertical stricture of tropical precipitation. After numerous tests and calibrations in the UK, the radar was shipped and installed at the University of Technology in Papua New Guinea (PNG). A continuous observation campaign began in Dec. 1995 and six months of data were collected. The radar recorded height and time variations of co-polar reflectivity, cross-polar reflectivity and Doppler Spectra.

As part of an ESA/ESTEC program, the Politechnico di Milano has developed a model for the melting layer in stratiform precipitation. The anisotropic model of the melting layer takes into account the meteorological models previously developed by a number of earlier studies. In its implementation, the equivalent diameter and the initial density of the melting layer ρ_0 of the melting particles are input parameters. From the top of the melting layer, the melted mass fraction is computed in 10 meter steps down to the bottom of the melting layer.

We report here the recorded Doppler spectra and the model predictions for Lae type climate. Data taken in the UK during the test phase (prior to shipment to PNG) show excellent agreement with the model predictions. Data recorded in PNG show very strong melting layer centered around a height of 4.5 km in stratiform precipitation. The co and cross-polar reflectivities show the usual enhancements and the Doppler mean velocity and the spectral width show the corresponding increase. The pulse-to-pulse time series data were analyzed to yield the full Doppler spectra and they will be compared with model predictions for a full assessment of the applicability of the model to tropical climates.

Session L07
Thursday, July 16, AM 08:40-11:40
Room R01
Indoor Propagation

Chairs : J. F. Diouris, S. Salous

Simulation of Adaptive Antennas in Indoor Environments by Using Ray-Tracing

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The increasing demand for wireless communication services is forcing to enhance the capacity and quality in cellular networks. Nowadays it's well known the interest in the application of adaptive antennas in wireless communications.

Basically, we can distinguish two types of DBF (Digital Beamforming) techniques, one based on temporal references and called TRB (Temporal Reference Beamforming) and other based on spatial references and called SRB (Spatial Reference Beamforming). In the assumption of using a spatial reference, an estimation of the direction of arrival from the signal is needed. However, in an indoor channel it exists a great dispersion in the directions of arrival, forming these a continuous distribution that varies quickly from one point to another and, furthermore, it is possible that there isn't a clearly preponderant direction of arrival with respect to others. Nevertheless, adaptive antennas can be used in indoor environments as a way to increase the system capacity and quality. In this case the solution consists of opting for adaptive algorithms based on a temporal reference.

One of the main elements to simulate the adaptive antenna behaviour is the channel model that is used. Taking into account that the directions of arrival are of importance in the simulation of the antenna performance in a multipath environment, a model based on ray-tracing methods seems very adequate. A site-specific channel model has the advantage of permitting the simulation of the antenna in different environments, considering the peculiarities of these without need of accomplishing exhaustive measures. In our case the radiochannel is obtained from a site-specific model that takes into account the following paths between the transmitter and the receiver antenna: direct ray, multiple reflections up to fourth order, diffractions, double diffractions, and reflected-diffracted and diffracted-reflected rays.

Furthermore, in this communication it is shown how a six element array antenna is able to improve the performance of an indoor communication system (QPSK modulation with a 20 Mbit/s rate). The adaptive antenna provides the capacity of reducing multipath dispersion and cochannel interferences, and it allows a better quality of service, reducing the bit error rate.

UHF Indoor Measurements

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Due to the high bandwidth requirements of indoor propagation, most reported wideband indoor measurements are obtained using network analyzers. Although a network analyser enables the measurement of power delay profiles with fine time delay resolution, its application to indoor measurements has two limitations. Firstly, the range over which these measurements can be conducted is limited since the analyser is used both to generate the swept waveform and to detect it; hence a cable is required to link the receive antenna to the analyser. Secondly, the time which is needed to generate the sweep does not enable the measurements to be carried out at a high repetition rate which necessitates taking the measurements at a time when the environment is stationary. To avoid these limitations PRBS sounders with bandwidths from 70 MHz to 90 MHz have been used. Alternatively, these measurements can be conducted using chirp sounders which employ frequency agile synthesizers, hence producing sweeps with adequate bandwidths and repetitions rates.

Indoor measurements were carried out using a chirp sounder developed at UMIST which is capable of generating sweeps up to 90 MHz at a fast repetition rate. The measurements were conducted at 1.8 GHz where the transmitter was placed on the fourth floor of an 8 storey building and the receiver was mounted on a trolley which was pushed around the corridors of the fourth and third floors. Subsequently, the data were analysed to determine the channel descriptors which include the average delay spread, rms delay spread, and the 10 dB and 15 dB widths of the profiles.

The results show the effect of channeling between floors and lift shafts, and the effect of neighbouring buildings on the channel parameters. In this paper, results obtained from these measurements will be presented.

Indoor Propagation Measurements : Propagation Between Floors

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The aim of this paper is to present results of indoor measurements done in 900 MHz frequency region. Measurement system comprises of a continuous wave (CW) transmitter, a measurement receiver and antennas with cables and connectors. Measurements are done in two different types of buildings. First building is characterised by open space, landscape offices, many walls covered with glass and direct Line-Of-Sight (LOS) and reflection connections between the floors. Second building is characterised by small office rooms, narrow corridors and no direct LOS connections between floors. We have measured the direction of incidence and field strength when transmitter and receiver are located in different floors. Results are used analysing both propagation environment and propagation models. The results show that it is easier to predict field strength in second type of building. This is due to smaller ceiling losses in that building, which causes that the direct path propagation is one of the major components in all measured floors. The direction of incidence measurements show that reflected and diffracted propagation paths are important. In first building open gap between the floors seems to be a major propagation path. In second building where no open gap between floors exists the major propagation path is not so clear. It seems that in lower floors, when there is only a few ceilings between transmitter and receiver, the direct path is a major component. Increasing number of ceilings results in upper floors that the propagation path through windows seems to be the dominating component. Two propagation models are studied: Multi-Wall and diffraction model. Results show that Multi-Wall model predicts field strength better than the diffraction model. The Multi-Wall model can predict the field strength satisfactory, rms-error around 7 dB, in both buildings. The rms-error of diffraction model seems to be very environment sensitive, meaning that in second type of building, the rms-error is around 7 dB, but in first building prediction of the field strength is poor.

Comparison Between Two Geometric Indoor Propagation Models : Tube Launching and Ray Launching

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In this paper, we present a comparative analysis between *ray-launching* and *tube-launching* techniques for modelling propagation inside buildings. It's explained briefly how both algorithms work, focusing on the problems that arise when modelling three–dimensional structures. Based on this idea, we expose some advantages and disadvantages of each method in efficiency and accuracy of results.

Ray Launching consists of the shooting, in the entire 4π stereoradians space, of straight rays that propagates from the transmitter according to the Geometric Optics (GO) theory. The total received signal strength is created as a result of the superposition of arriving magnitudes and phases of individual rays in the receiver. The principal advantage of this method is the easy implementation in a computer. If a ray intersects a reception sphere, with a defined radius (*the impact radius*) around the receptor, it is considered that contributes to the total received signal. For good result accuracy, it is desirable that rays launched from the transmitter maintain a constant angular separation from its neighbour rays. This ensures that each ray represents an equal, regularly shaped, and unique portion of the total spherical wavefront.

The impact radius r must effectively account the divergence of the rays from the transmitter. If r is oversized, more than one ray from the same wavefront will be added wrongly to the total received power. If it's undersized, the rays of the same wavefront will not reach some receivers. This problem could be solved with an algorithm that verifies for each received ray if there's any other previous received ray with similar direction. If this happens, the new received ray may be adjacent to the previous, and it hasn't to be considered. Another possibility is the use of weighting functions that weight the power levels of received rays, so that the redundant contributions will be compensated. The selection between both methods depends on some simulation parameters like number of transmissions/reflections for each ray, wide-band or narrow-band design, etc.

Tube Launching is a variation of ray launching where we launch structures like rays, but with three dimensions: tubes. One tube is made with several rays. Each one forms the surface edge that limits the tube. The tube influence zone is limited by these surfaces, so it's unnecessary the impact radius, because the power associated to the tube is added to the receptors located inside it.

Tube use is problematic in complex and high dimension environments (like office buildings). In a high dimension building, tubes will travel large distances. It's not rare that an obstacle will only intercept a fraction of the tube, involving that the tube has to be divided in several (*splitting*), spending more simulation time. Alternatively, we could discard this tube, resulting on worst results.

Tube launching increase simulation speed against ray launching, especially for high levels of reflection/transmission simulation environments. Tubes are also better in places close to thin surfaces like partition walls. However, ray launching could work better in complex environments with high number of obstacles and surfaces with small size holes, zones next to corners or high dimension environments. On the other hand, tube launching could be better for *in–room* situation, like small dimension rooms or closed environments with moderated dimension. A sensible choice will depend on the specific simulation environment.

A Hybrid Method for Indoor Propagation Modelling

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A hybrid Parabolic Equation-Ray Optical Model, abbreviated as PERO model is developed in this paper. Ray Tracing, Local Mode and Parabolic Equation approaches have been utilized by several authors for indoor propagation modelling. There are two methods to account for transmitted electromagnetic energy from neighboring rooms. One of them is Ray Optics method and the other is Parabolic Equation method. Ray optical description is efficient if the field is to be calculated at a small number of potential receiver locations. Local Mode and Parabolic Equation methods advance the given field distribution on an initial surface to another surface, however, it must be close to the initial surface. Parabolic Equation method is preferred when the transmitter and the receiver are in different rooms and when the propagation to receiver locations of interest is predominantly paraxial with respect to a preferred (axial) direction. However, in arrival time calculations PE becomes inefficient, since computations must be performed in the frequency domain.

In this paper the advantages of hybrid techniques based on ray tracing and parabolic equation methods are investigated and attempted to combine strong sides of both methods. In our analysis, a deterministic Ray Tracing propagation model is used to account for the transmission of the electromagnetic energy from neighboring rooms and floors. This model connects the transmitter and receiver located in different rooms or floors via well defined ray paths either directly or after a number of reflections and transmissions from walls. Two neighboring empty rooms are considered and via the conventional image based Ray Optical model, the electric field component corresponding to waves propagating into room 2 is calculated somewhere in the second room(on the middle surface of second room) considering up to three reflections. On each wall of the second room along the axial direction(the common wall and the opposite wall of it), the electric field distribution is calculated by the forward and backward propagating components. According to the PERO method, the initial fields on each wall are advanced in steps of Δz in both directions and the electric field distribution is found as a superposition of backward and forward propagating paraxial spectra on the middle surface of the second room.

This distribution is compared to the distribution found by Ray Optics. Finally, the validity of PERO model is verified with this comparison. Combination of Ray Optics with Parabolic Equation propagators is succeeded. The results indicate that this hybrid method is both accurate and efficient, and valid when transmitter and receiver are well separated and are located in different rooms.

Characterization of Indoor Propagation and Building Components Loss Factor

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The development of radio indoor communications and wireless networks, such as cellular mobile phones, Personnal Communication Systems or Local Area Networks, needs the knowledge of indoor propagation and building components characteristics.

Indoor radio propagation presents special difficulties : refraction, diffraction, scattering of propagation paths, noise, cochannel interferences. Usual techniques for predicting electromagnetic propagation in buildings are empirical methods and ray tracing approaches. Empirical methods use path loss prediction formula which are adapted to measured data. Ray tracing are deterministic approaches for predicting attenuation or impulse response. The main difficulty in such methods is the high number of inputs needed : dielectric permittivity and conductivity of each wall have to be known.

We propose a new method to characterize indoor propagation and wall characteristics. Our approach is based on energetical and statistical principles with the hypothesis of a diffuse field propagation. Power density within building is calculated by considering energetical balance between the different rooms.

This leads to consider the wall electromagnetic loss factor in a diffuse field. This factor, very useful, is independant of incidence angle or polarization, and can characterize any heterogeneous wall.

A measurement method of electromagnetic loss factor has been developed, using two reverberating rooms. Its protocol and principle have been validated between 200 MHz and 20 GHz by measuring and modeling the loss factor of metallic grids of different sizes. Then, measurements of usual building components have been performed.

Statistical Model and Simulation of Indoor Channel Propagation in 1.8 GHz

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The progress of mobile radio communication systems is capable to provide a significant proportion of population with access toward wireless personal communications. Presently, field trials are being conducted throughout the world to determine the suitability of various modulation, multiple-access and networking techniques. To develop more performance systems, however, we need good knowledge of multipath propagation phenomena in either outdoor or indoor environment.

This study presents the results of propagation measurements, which have been performed to characterize indoor radio channel in 1800 MHz band. In practice, a wide band channel characterization can be obtained either in the time domain (by measuring the impulse response), or in the frequency domain (its transfer function). The frequency domain technique using PC based measurement system has been built around a vectorial network analyzer.

The characterization is realized in two main categories : large and small-scale models. A large scale characterization consists of the path power loss evaluation in function of the distance between transmitter and receiver. This measurement results are particularly applied on estimating the radio coverage for a certain system.

A small scale characterization allows to show us the existence of multipath fading. In taking some considerations, these techniques allow the receiver to have the channel impulse response. The delay dispersion parameters are then characterized from the measured power delay profile. These parameters are useful in estimating the maximal data rate in digital transmission.

The coherence bandwidth of the channel (B_c) which is a measure of the similarity or coherence of the channel in the frequency domain, is also determined. It is conversely proportional to its delay dispersion. It gives a first indication of the selectivity of the channel. When B_c is a much greater than the bandwidth of the useful signal, selective effects will be negligible and the narrow band effect become dominant. The above characterizations have been under taken in different types of environments : office, exposition hall and industry.

Other measurements have concerned with the influence of movement in building on the parameters that characterize the propagation. The measurements have been undertaken in normal movement conditions of persons of the laboratory. In this case, movements are mainly due to displacement of researchers, students, personnel, visitors, etc.

Based on the measurement results, a channel model is then developed within the framework of simulation on digital communication systems using *PTOLEMY*. This simulation validates the choice of a *RAKE* receiver design which is suitable for indoor channel propagation.

The described analysis concern the first results of the measure. Other measurements are again necessary to enrich our data base, in example by using several types of antenna, or by undertaking measures in other types of building, or by studying characteristics of materials of the furniture and partitions, etc... The statistical analysis of the data will allow then to end to a realistic model of the indoor channel. This channel model will be a great usefulness to design high performance communication systems.

An Efficient Method to Analyze Radiopropagation in Enclosed Spaces Combining Image Theory with BSP

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New services and wireless communication systems of increasing bandwidth are emerging, taking advantage of the flexibility achieved by elimination of cabling. The design planning and installation of this kind of wideband services as well as the research in future WLAN's and PCS's applications, need not only CAD tools for coverage calculation but that are also capable of estimating radio channel performance.

A flexible approach to the radiopropagation mechanisms allows the analysis of a great number of man made environments. In indoor and urban environments the scatters can be modeled in detail using flat patches. The edges between pairs of these surfaces are also included defining a facet-edge model. Different scenes like within buildings, underground installations, tunnels and urban pico and microcell can be analyzed. The approach is based on an efficient ray tracing method in combination with several electromagnetic models of the environment. This model has been implemented in a computer code named Cindoor based on a site-specific model of radio propagation, employing the ray or high frequency approach with a 3D implementation of the Geometrical Optics and the Uniform Theory of Diffraction (GO/UTD) approach.

The coupling between the transmitting and receiving antennas being obtained as the contribution of different scattering mechanisms, such as direct field, multiple reflections, edge diffractions and combinations of these (diffraction-reflection, reflection-diffraction, etc.). An efficient method to perform the ray-tracing is a basic requirement to make an efficient code. This problem has been solved by using a combination of the image theory with the BSP (Binary Space Partitioning) algorithm. The BSP is a widely used technique in the computer image processing and animation fields. Using this technique it is possible to determine when a plate is shadowed by the other plates of the model. The main advantage of the BSP algorithm is that, unlike other methods as the z-buffer, the generation of the binary tree is independent on the relative positions of the transmitting and receiving antennas.

Finally, once the space-temporal distribution of the field is known, this signal is processed to obtain parameters of interest for system design and performance evaluation such as coverage maps, fading statistics, power delay profile, RMS delay and coherence bandwidth.

Session M06
Thursday, July 16, AM 08:40-11:00
Room R03
Medical Applications

Organiser : A. Mamouni

Chairs : A. Mamouni, S. Mizushina

Iterative Magnetic Current Reconstruction from Cylindrical Acquisition

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A source reconstruction method based on the knowledge of the tangential electric field components over a cylindrical surface is presented.

According to the equivalence theorem and image theory an external equivalent problem is defined in such way that only magnetic currents are defined over an infinite plane enclosing the real radiating sources (e.g. the antenna under test). In practice the infinite plane is truncated to the extension where the field level is significant.

Near field radiation integral equations in an unbounded medium can be used to relate magnetic currents and the acquired field.

The relevance of this method is that the magnetic current components over the plane are calculated at different and consecutive steps, since the proposed formulation makes possible to estimate sequentially each magnetic current component from only one component of the electric field. That means that the number of unknowns at a time is the correspondent to only one component of the magnetic current.

An optimization procedure is used for the determination of each magnetic current component from the known tangential field components.

A Levemberg-Marquardt algorithm is implemented to minimize the cost function regarding the difference between each acquired field component and the same component of the theoretical field radiated by the equivalent magnetic currents at each aspect angle.

If the near fields are known over a complete cylindrical surface, at least two planes (forward and backward equivalent problems) with different sets of equivalent magnetic current are needed to characterize the radiation at every azimuth angle.

The method is directly applicable to near field - far field transformation , allowing the calculation of 3D antenna pattern by the source representation of the antenna from its cylindrical surface near fields.

Some results using synthesized data will be presented to check the feasibility and effectiveness of the proposed method.

This work was performed under the auspices of the Comisión Interministerial de Ciencia y Tecnología of Spain under contract TIC95-0123.

Design and Optimization of Short Antennas for Phased-Array Hyperthermia Applicator

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The radiofrequency regional hyperthermia (RF-RHT) is an adjuvant therapy method for deep-seated tumors. Because of the limited penetration of the electric fields, annular phased arrays (APA) of eight water-loaded antennas are designed to interfere constructively inside the patient [1]. In pelvis applications one ring of approx. 60 cm length with tapered flat dipols is used. Unfortunately, the dielectric boundaries of different water content tissues (eg. muscle and bone) cause high elevations of the E-field, perceived by patients as painful hot spots. Numerical studies have shown that these hot spots can be better resolved when instead of the single ring the APA is axially segmented into three rings [2]. Unfortunately, shortening antennas to approx. 20 cm considerably reduces their efficiency (low input impedance, charge related high normal electric field at patient's skin) and therefore measures are to be taken to maintain their radiation performance.

On the other hand, an interaction-free combination of the RF-RHT applicator and the magnetic resonance (MR) tomograph is aspired in order to noninvasively monitor the temperature in patient during treatment. For the reason of MR compatibility, the conventional electrical antenna lengthening solutions based on loop and flat structures cannot be applied.

To improve the efficiency of short antennas as radiation elements of axially segmented and MR compatible APA the principle of mirroring at the magnetic wall created by the water/air interface was applied. Accordingly, the single dipoles in front of the magnetic wall behave like the folded dipoles, considerably increasing the feed-point impedance. An additional bending the dipole ends away from the patient towards the magnetic wall reduces the normal E-field at patient's skin and introduces the top capacity which further lengthens electrically the antenna. In addition, the cylindrical performance of this structure offers an attractive solution for current balancing with chokes and/or double-chokes as well as an elegant and shielded guidance of feed cables for all three segments inside the antenna tubes.

Using this „quasi folded“ dipole as a basic structure, numerical calculations and optimization of the single element, the axial row of three elements, the ring of eight elements and the entire segmented applicator were carried out. As a numerical tool the volume surface integral equation (VSIE) method was aplied [3]. The VSIE is a generalization of the method of moments (MoM), which allows for treatment of the inhomogeneous media. The optimization was performed using the procedure of simulated annealing. The parameters were the distance to the water/air interface, the thickness and the length. The goal was to minimize the return loss, the normal E-field and the mutual coupling. The numerical results were verified by measurements.

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Numerical Studies of Electromagnetic Compatibility for Combination of Phased Array Hyperthermia Applicator and Magnetic Resonance Tomograph

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The therapeutic radiofrequency regional hyperthermia (RF-RHT) of the deep-seated pelvic tumors requires a noninvasive monitoring of temperature. Methods of magnetic resonance (MR) thermography seem to be the most suitable solution [1]. Therefore, an interaction-free combination of the RF-RHT and MR systems is necessary. At present, the best established RF-RHT applicator is the annular phased array (APA) of axially aligned water-loaded dipoles, which is designed for the constructive interference of the axial electric near-field at the depth of tumor [2]. For the reason of an optimal penetration of the electric field, the APA for pelvis application operates in the frequency range near 90 Mhz.

There are two conceptually different types of MR tomographs which can be considered as candidates for the combination with the APA. The high performance mid and high field tunnel systems operate at frequencies not far from the APA's 90 MHz running the risk of receive the high power irradiation from the APA, which can destruct the sensitive MR receiver system. The low vertical field MR tomographs with open magnet structure operate at lower frequencies and, although their rather low performance makes them at present less suitable for sensitive temperature measurements, they attract some attention for the combination with the APA, because the risk of destruct the MR receiver is considerably reduced by reason of large operation frequency distance. However, the MR loop coils arranged here for higher SNR close by patient's body, and thus close to the APA, can significantly impair the APA's functioning. The purpose of this contribution is to numerically investigate the mutual parasitary influence as well as the RF interactions between the APA and the two different MR systems.

The numerical simulations were performed using the finite-difference time-domain (FDTD) method and were verified for special cases by the volume-surface integral equation (VSIE) method [3]. The APA's antennas were modeled as dipoles inside the water bolus surrounding the realistic 3D homoid phantom. Each MR tomograph was represented only by its typical RF environment, ie. the shield tube and the saddle coil outside the APA in case of the tunnel type and the pole shield and the axial loop coil in case of the open type.

Simulation results for the tunnel type MR tomograph demonstrate that the mutual arrangement of the APA's antennas and the MR body coil does not affect significantly the APA's functioning. In contrary, the arrangement of the axial loop coil of the open MR tomograph in relation to the APA can considerably influence the performance of the combined system.

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Fan Beam Based High Speed Imaging of the Chirp Radar-type Microwave Computed Tomography

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For practical use of the chirp radar-type microwave computed tomography(1), techniques for quick data acquisition are strongly desired. As was described in our preceding paper(2), [1] shortening of the sweep-time of the chirp signal, [2] use of electronic scan of the antennas instead of the mechanical scan, and [3] simultaneous measurement at several points can contribute to the fast data acquisition. In the study, high speed imaging has been attempted based on electronic scan of the antennas for collecting the projection data. The microwave chirp signal from 1 GHz to 2 GHz is radiated from a dielectric loaded waveguide antenna whose half power beamwidth is wider than 90 degree. Thus, the fan-beam projection is assumed, regardless of the electromagnetic wave. To collect the projection data, twenty one dipole antennas of a half wavelength are arranged in a circular shape as shown in Fig. 1. Projection data is consisted of 21 line integrals of the attenuation constant between the transmitting antenna and each of those dipoles. To collect the projection data from a specific direction, only electronic scan is needed. In reverse, mechanical scan of the antenna unit which is referred to as rotational scan is also needed for tomographic imaging. Tomograms are reconstructed by a convolution method for divergent beams(3).

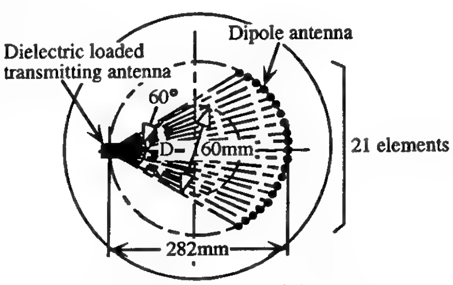
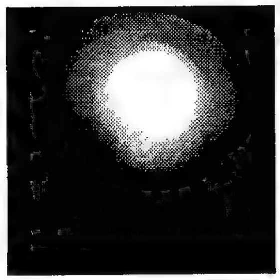


Fig. 1 Configuration of the scanner

Figure 2 is an example of the attenuation image reconstructed from 200 projections. Each of projection is, of course, consisted of 21 attenuation data. In response to the reduced information of the projection data



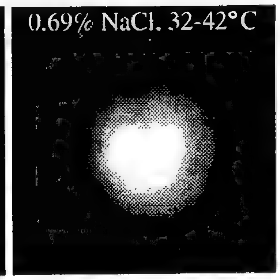


Fig.2 An attenuation image

Fig.3 Imaging of temperature chnage by 10 °C

(less than 66%) as compared to T-R scan, the roughly estimated spatial resolution has been degraded. However, temperature imaging is also possible as shown in Fig. 3.

The fan beam based imaging technique has an advantage of the fast data collection. At the same time, problems of its narrow measurement field, coarse spatial resolution, and inhomogeneous sensitivity of the measurement field must be solved. However, the high speed imaging capability which completes data collection within one minute is a big advantage of the imaging system.

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Amplitude Modulation Based Fast Data Acquisition of the Chirp Radar-type Microwave Computed Tomography

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A prototype system of the chirp radar-type microwave computed tomography whose spatial resolution is approximately 1 cm and the minimum detectable temperature difference is 0.3 - 0.5°C has been developed for noninvasive thermometry of the human body(1-3). However, it takes about 90 minutes for tomographic measurement, because projection data are collected by mechanical scan of a single transmitting- and receiving-antenna unit. For clinical application, the data acquisition time must be reduced. Key technology for fast data acquisition would be, [1] reducing the sweep-time of the chirp signal, [2] use of electronic scan of the antennas instead of the mechanical scan, and [3] simultaneous measurements at several points in the field. Modulation scattering technique which satisfys [2] and [3] has been employed for tomographic measurement.

As shown in Fig. 1, diode-loaded small dipoles are arranged in front of the receiving antenna and modulate the chirp signal at each point with low frequency signals whose frequencies are slightly different to one another. Beat signals between the input signal and the transmitted signals which are modulated with those dipoles appear at slightly different frequencies due to the difference in the modulation frequency. Since those transmission paths of the chirp signal are distinguished from frequency of the modulated beat signal. Thus, amplitude of the signal transmitted on each straight path is measured by spectral analysis of the modulated beat signal.

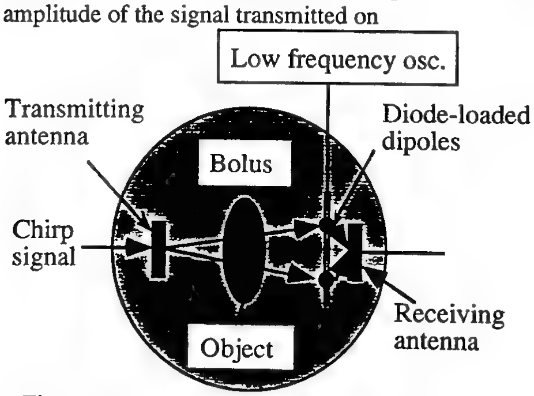

Fig. 1 Measurement by modulation scattering

Figure 2 shows an example of tomographic imaging of a phantom and temperature difference obtained by modulation scattering. Instead of slight degradation in the SN ratio, simultaneous measurement at three points has been successfully accomplished. It takes approximately 1.9 minutes for data acquisition in such a system. This would be enough for imaging of a biological target. Temperature imaging by microwaves has an essential advantage that the temperature image is free from the change in blood flow rate inside a human body.

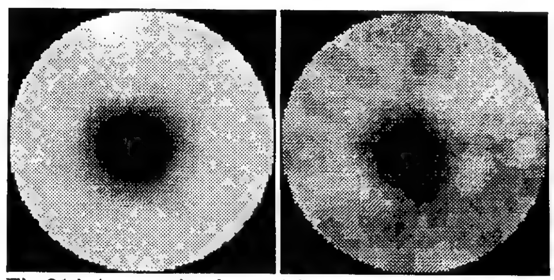

Fig.2(a) Attenuation image Fig.2(b) 5°C-temperature difference image

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A part of the study is supported by the grant in aid for scientific research (#09558116) by the Japanese Ministry of Education.

Electromagnetic Fields Induced Inside Human Tissue : an Analysis Using Solenoidal Basis Functions

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In this work we use a volume formulation to analyze the problem of electromagnetic induction inside biological bodies of arbitrary shape. The method of moments is applied to solve the integral equation with the use of tridimensional solenoidal basis. The use of the Method of Moments with volume basis functions to analyze the scattering of EM waves has always suffered from convergence problems. To overcome this problem in the scattering of waves in two dimensions, Mendes and Arvas used a solenoidal basis function to eliminate the spurious charges and obtained good results for high values of the dielectric constant. Mendes and Carvalho, extended this solution to analyze tridimensional problems. In this paper we present results showing the effectiveness of this method to evaluate the electromagnetic fields induced inside human bodies. Figures 1 and 2 show the results of the electromagnetic fields induced inside human tissues. Figure 1 shows the fields inside a muscle and Figure 2 shows the fields inside a fat cylinder. In both figures the cylinders are illuminated by a plane wave at 2.45GHz and we consider the homogeneous and the inhomogeneous cases. These results are in good agreement with published literature.

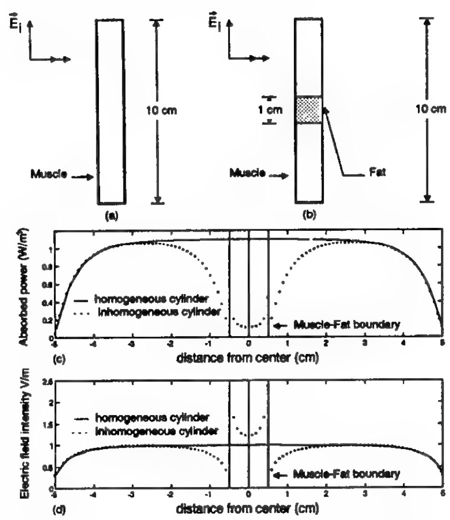

Fig. 1 Cylinder illuminated by a plane wave of 2.45GHz, partitioned into 600 tetrahedrons.
Muscle $\varepsilon = 47\varepsilon_0$ $\sigma = 2.21\,S/m$
Fat $\varepsilon = 5.5\varepsilon_0$ $\sigma = 0.15\,S/m$
(a) Homogeneous muscle cylinder.
(b) Inhomogeneous muscle cylinder.
(c) Electric field along cylinder axis. $\mathbf{E}^i$ is 1 V/m.
(d) Power density $(1/2\sigma|\mathbf{E}|^2)$ along cylinder axis.

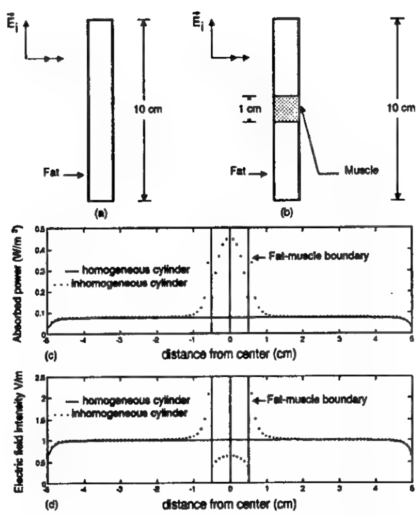

Fig. 2 Cylinder illuminated by a plane wave of 2.45GHz, partitioned into 600 tetrahedrons.
Muscle $\varepsilon = 47\varepsilon_0$ $\sigma = 2.21\,S/m$
Fat $\varepsilon = 5.5\varepsilon_0$ $\sigma = 0.15\,S/m$
(a) Homogeneous fat cylinder.
(b) Inhomogeneous fat cylinder.
(c) Electric field along cylinder axis. $\mathbf{E}^i$ is 1 V/m.
(d) Power density $(1/2\sigma|\mathbf{E}|^2)$ along cylinder axis.

Session A08
Thursday, July 16, PM 13:40-18:00
Room 300
Coherent Effects in Random Media II

Organiser : V. Freilikher
Chairs : V. Freilikher, H. Ogura

Scattering of Two-Dimensional Random Heterogeneous Media : Comparison of Radiative Transfer and Electromagnetic Numerical Simulations

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The radiative transfer theory has been extensively applied to deal with the radiation-heterogeneous media interactions when scattering appears. These calculations rely on some approximations : interference terms are neglected, the scatterers properties are defined independently. In order to check the validity of this approximation, we have developped a numerical simulation that accounts for the transfer problem itself. Previous numericl simulations have beenrestricted to the determination of the scattering properties of random media (i.e. the phase function and the extinction coefficient). In order to be able to deal numericall y with the transfer problem through a slab, we consider a two-dimensional problem. On one hand, we have implemented the discrete ordinate approximation to solve the Radiative Transfer Equation (RTE), that describes the spatial evolution of the specific intensity. We obtain collimated or diffuse irradiances, and the Bidirectionnal Reflection or Transmission Distribution Function (BRDF and BTDF). On the other hand, we use a Method of Moments (MM) to solve exactly an integral formulation of the scattering problem. This yields the *electromagnetic field*, for a deterministic realization of the random system. After ensemble average on N different realizations, we obtain the coherent and incoherent intensities so that we can derive the BRDF and BTDF.

We have used these two methods to compute scattering by randomly distributed, perfectly aligned, infinite cylinders illuminated perpendicularly to their axes. The reciprocity of the BRDF is found with both methods. Comparisons for tenuous and thin media between diffuse BRDF (RTE) and incoherent BRDF (MM) are in very good agreement. A difference is seen for the forward scattering when comparing the two methods. This point will be discussed.

For optically thick media, enhanced backscattering appears in the numerical simulation. The coherent forward single scattering and enhanced backscattering can be taken into account by the radiative transfer method after small modifications. When the volume fraction is increased the agreement is not good due to dependent scattering. We can derive the effective complex index of the diffuse medium from the nuemrical simulations.

Experimental Study of Light Scattering by Well Characterized Two-Dimensional Randomly Rough Dielectric Surfaces

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In order to understand the scattering of light on rough surfaces, we have fabricated well controlled two-dimensional surfaces and studied their optical properties at visible wavelength.
We present the fabrication of these samples using a technique similar to that used in the micro-electronic industry.
The scattering material is a thin photoresist film, spin coated on a flat glass substrate, baked in an oven and exposed to an Argon laser (UV illumination at 363 nm).
The surface of the samples is characterized on an AFM (Atomic Force Microscope) in order to obtain the surface profile, the roughness properties and the correlation length.
The samples are then studied on a bidirectional reflectometer and we measure their BRDF (Bi-directional Reflection Distribution Function) in the visible. The source is a HeNe laser, working at 633 nm and the angles of measurement can vary from less than half a degree away from the incident beam direction out to 85 degrees from the normal to the glass substrate.
The experimental results will be compared with the mean-field theory recently developed from modeling scattering by two-dimensional randomly rough dielectric surfaces.

Scattering from an Object on Random Rough Surface - Stochastic Green Function -

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From both theoretical and experimental point of view, the scattering from a target on a random surface is an interesting problem particularly in connection with the backscattering enhancement arising from the double scattering between the target and the random surface. Such a scattering problem can be readily and systematically formulated by means of the stochastic Green function that already satisfies the boundary condition on the random surface. The stochastic wave field for a plane wave injection was obtained in terms of Wiener-Ito expansion for the Dirichlet and Neumann random surface, and the stochastic Green function was also represented as an integral over a path on the complex plane as well as its asymptotic form at a distant observation point [1,2]. In this paper we assume a definite object above the random surface, and just like an ordinary scattering theory we can establish an integral boundary equation on the object surface in terms of the primary field and the stochastic Green function, both functions already satisfy the boundary condition on the random surface which no longer bothers us in the integral equation. The simplest solution is the «single» scattering approximation in terms of the stochastic Green function which automatically involves the scattering effect over the random surface, and consequently this «single» scattering already involves the double scattering process via the random surface and the object. By asymptotic evaluation of the stochastic Green function we can easily estimate the angular distribution of the scattering from the object which give rise to a backscattering enhancement much stronger than those arising from the «double» scattering process over the random surface. Calculations are made for a point-like and cylindrical object above random surface at various altitudes.

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Frequency-Angular Correlations of the Intensity of Scattered Wave from a Random Surface

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The intensity correlation of rough surface scattering has attracted considerable attention in connection with the memory effect in the angular correlations satisfying the condition $\sin\theta_0 - \sin\theta_s = \sin\theta'_0 - \sin\theta'_s$, θ_0 and θ_s denoting the incident and scattering angle, respectively.

In the present paper, we discuss on the cross-correlations between the angular intensities of the scattered waves with different frequencies by means of the stochastic functional approach. Assuming the random surface to be a homogeneous Gaussian random field, the stochastic wave field is represented as a Wiener-Ito expansion [1], where for small roughness, the «single» scattering process described by the first Wiener kernel gives a good approximation. Using the «single» scattering term, we easily obtain the stochastic anglular intensity $I(\theta_s|\theta_0, f)$ where f denotes the frequency of the incident wave. The cross-correlation between $I(\theta_s|\theta_0, f)$ and $I(\theta'_s|\theta'_0, f')$ demonstrates the correlation or memory where the condition $f(\sin\theta_0 - \sin\theta_s) = f'(\sin\theta'_0 - \sin\theta'_s)$ is satisfied. In a special case of $\theta_0 = \theta'_0 = 0$, we see that the speckle patterns with different frequencies has correlation in such a way that $f\sin\theta_s = f'\sin\theta'_s$. Generally speaking, we expect that the memory line due to the above memory equation is formed in the angular correlation between the speckle patterns of different frequencies for a fixed incident angle, which we can call «the frequency-angular memory effect». This memory effect is largely due to the same Bragg vector of the random surface. In the single scattering we expect that because of the intensity correlation the reversed Bragg vector can also produce the correlation, in such a way that $f(\sin\theta_0 - \sin\theta_s) = -f'(\sin\theta'_0 - \sin\theta'_s)$. We point out that measuring the frequency-angular memory with a fixed incient angle with varying frequencies is sometimes easier than the ordinary angular memory observation with changing incident angle, because changing incident angle creates the variation of illuminated area which is difficult to fix.

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Backscattering Enhancement in the Scattering from a Cylindrical Random Rough Metal Surface

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The phenomenon of enhanced backscattering, manifested as a well-pronounced peak in the anti-specular direction in the angular distribution of the waves incoherently scattered by random rough surfaces, has attracted a great deal of attention in recent years. It has been believed that the mechanism responsible for the enhanced backscattering is the coherent interference in the multiple scattering processes, and for slightly random rough surfaces, the participation of unstable or stable surface waves as the intermediate scattering processes is very important to produce such enhanced backscattering. Most of the studies, however, have been concentrated on random rough surfaces in a planar geometry.

In this presentation, the scattering of a scalar plane wave from a metallic cylinder with a slightly random rough surface and the effect of surface plasmon waves supported by the cylindrical metal surface on the enhanced backscattering are studied by means of the stochastic functional approach. The cylindrical random surface is assumed to be a homogeneous Gaussian random field, homogeneous with respect to the group of motions on the cylinder, i.e., translations along the axis and rotations around the axis. The random scattered wave field is regarded as a nonlinear stochastic functional of the cylindrical random surface, and can be represented as a Wiener-Ito expansion in terms of the Wiener-Hermite differentials and the cylindrical wavefunctions. The expansion coefficients up to the second order are determined by the approximate boundary conditions for small roughness. Various statistical characteristics of the scattered wave are obtained from the stochastic wave field, by making use of the orthogonality of the Wiener-Hermite differentials. Some numerical calculations are shown for the angular distribution of coherent and incoherent scattering.

Near-field and Far-field Changes in the Spectrum of Light Scattered from a Randomly Rough Surface

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As was recently shown [1], the frequency spectrum of light scattered from a random surface undergoes changes that bear the signatures of coherent multiple scattering phenomena. Namely, if a one-dimensional randomly rough surface bounds a system that supports several guided modes than the angular dependence of light multiply scattered from this system exhibits the enhanced backscattering peak and the satellite peaks, and the angular positions of the satellite peaks are frequency dependent. This frequency dependence gives rise to the marked features in the spectrum of scattered light at the angles where the satellite peaks occur. In addition, there is a smaller effect in the vicinity of the backscattering direction. Subtle physics of these spectral changes lies in the correlation of secondary sources located the randomly rough surface, and present a manifestation of the Wolf effect discovered in 1986 [2].

In this work, we extend the analysis of Ref.1 given in the weak roughness limit, to the case of rougher surfaces. To study this case, we use Monte Carlo simulations based on the formally exact method of moments instead of the small-amplitude perturbation theory used in Ref.1. We consider the scattering of p-polarized Gaussian beam from a randomly rough film on a perfectly conducting substrate. The system is assumed to support several guided modes at the frequency of the incident light. As in Ref.1 we study the far-field spectrum of the scattered light at different angles of incidence and scattering and analyze the changes with respect to the spectrum of the incident wave. But, in addition to that we look at the near-field spectrum of the scattered light. In contrast to the far-field spectrum, which includes contributions from the propagating waves, the near-field spectrum includes contributions from both propagating and evanescent components. This calculation allows studying spectral changes of scattered light on propagation. Finally, we analyze similarities and differences between the spectral changes of light scattered from the systems bounded by weakly rough and strongly rough surfaces.

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Incoherent Acoustic Imaging in the Ocean

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The theory of optical incoherent imaging in the atmosphere is well known. In this paper we wish to discuss incoherent imaging of acoustic waves in the ocean. Buckingham et al1 have considered this problem but here we wish to approach the imaging from a coherence point of view and also study the effect of volume scattering. We begin by reviewing optical imaging in the atmosphere both from the usual perspective of a lens and from a coherence point of view. We present the basic relation governing incoherent optical imaging using a lens and then show how this relation may be interpreted in terms of the optical coherence function. The optical coherence function is defined in terms of the optical field and it is shown that the image intensity is the Fourier transform of the coherence function in the lens plane. Direct measurement of the coherence function may thus be used instead of a lens to create an image. By analogy we then consider the acoustic imaging of an object some distance below the ocean surface using coherence measurements on the ocean surface. First we formulate the problem in the absence of volume scattering. The acoustic incoherent imaging process is discussed five stages: (1) analysis of the incoherent source on the ocean surface, (2) propagation of the acoustic radiation from the source to the object, (3) reflection of the impinging acoustic radiation by the object, (4) propagation of the reflected acoustic radiation from the object to the detector at the ocean surface and (5) measurement of the coherence function by the detector and utilization of this measurement to determine the intensity of the object. Finally, we include the effect of random sound-speed fluctuations in the ocean on the incoherent imaging process.

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Impurity Induced Local Polariton States

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We consider dynamics of an ionic crystal with a single impurity in the vicinity of the polariton resonance. We show that if the polariton spectrum of the host crystal allows for a gap between polariton branches, the defect gives rise to a novel kind of local states. These states exist within a polariton gap of a material and are a mix of excitations of the crystal, such as phonons or excitons, and the transverse electromagnetic field. Despite the atomic size of the impurity we find that new local states are predominated by long wavelength polaritons. Electromagnetic component of the states along with the corresponding excitations of the material are localized in the vicinity of an impurity. Properties of these states are shown to be different from the properties of the well-known phonon or exciton local states. For instance, even in 3-D, localized polaritons appear when the difference between the mass of the impurity atom and the mass of an atom of a host crystal is infinitesimally small, and they disappear if this difference becomes too large. Such a behavior is due to the singularity in the density of states of polaritons near the low-frequency boundary of the polariton gap. Assuming cubic symmetry of the defect site we consider a complete set of the local states arising near the bottom of the polariton gap.

One of the experimental manifestations of the local polariton states could be the resonance tunneling of electromagnetic waves. The transmission rate of the tunneling waves should increase when its frequency coincides with the frequency of the local polariton state. In order to check this hypothesis we study numerically propagation of polaritons formed by a scalar electromagnetic wave and excitations of a finite one dimensional chain of dipoles. We show that an impurity dipole embedded in the chain causes resonance tunneling of the electromagnetic wave with the frequency within the polariton gap. We demonstrate that the tunneling occurs due to the local polariton state caused by the defect.

Transverse Spectra in Two-Way Wave-Propagation in Random Media

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Quasi-monodirectional propagation in a forward-scattering random medium is customarily treated by using the approximate *parabolic* formulation (PA) of the wave equation to track the range-evolution of transverse *spatial* statistics of the propagation signal. This approach is applicable when the directional spectrum of the signal broadens, e.g. due to cumulative effect of multiple scattering. When widely-scattered and backscattered radiation become important, recourse can be made to a *radiative-transport* (RT) formulation, whose use was originally advocated on phenomenological grounds, and later acquired a more rigorous basis through the use of diagrammatic summation techniques.

To derive mathematical models which span both of the aformentioned formulations, we manipulate the Helmhotz equation to address the range-evolution of the coupled transverse *spectral* statistics of the forward - and back-propagating components of the wave. This produces aquations for the ensemble-averages of the two field components and the four coherence functions which correlate them.

The treatement of the statistics pursues two variants of the local perturbations approach. One of these variants follows the « traditional » development, and produces (integro-) *difference* equations which are basically non-linear in range, but may be approximated by a linearized integro-diferential version under suitable conditions. The other variant reproduces an (integro-) differential model which maybe obtained directly by applying the functional (Novikov-Furutsu-Rino) formalism. However, the derivation does not invoke the restrictive assumption of a Gaussian propagation scenario, and instead exposes clearly the role of the caveats imposed by a finite range correlation-length. While it is still unclear why these caveats are not encountered when gaussianity is assumed, the latter development effectively extends the relevance of the functionalformalism to non-Gaussian media. The two models are different but inter-related : the integro-difference model (even in its approximate linearized form) is essentially a range-smoothed version of the integro-differential model, and lacks certain terms which are eliminated by the smoothing process. Both models conserve power.

These models account for wide-angle scattering and backscattering, as well as the often-neglected interaction between the radiative and evanescent components of the spectra. They reduce to the PA model in the regime of narrow-angle scattering, and to an RT model when the radiative-evanescent interactions are neglected. Moreover, they appear to be computationally tractablr, in that they can be « marched » in range, albeit with complications that arise from the fact that two-way propagation entails a two-point boundary-value problem in range.

To illustrate applicability and computational tractability, we consider the range-evolution of the forward and backscattered power flux spectra of a plane wave which crosses a slab with Gauss-distributed refractivity fluctuation. The results demonstrate the manner in which backscattering obliterates the asymptotic equipartition regime which would be approached if forward scattering alone were considered.

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Dispersion Relation for Electromagnetic Waves in a Stochastically Modulated Dielectric Superlattice

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Numerical studies are presented of the dispersion relation for electromagnetic waves propagating in a random one-dimensional dielectric system. The waves propagate in the x-direction, and the dielectric constant of the system is assumed to be a harmonic function of x with a stochastically modulated period, which we write in the form $\varepsilon(x) = \varepsilon[1-\gamma\rho(x)]$ [1]. Here $\varepsilon =< \varepsilon(x) >$ is the mean value of $\varepsilon(x)$, while $\rho(x)$ is a centered $< \rho >= 0$ and normalized $< \rho^2 >= 1$ stochastic function of x , so that $\gamma =< (\delta\varepsilon(x))^2 >^{1/2} / \varepsilon$ is the relative rms deviation of the dielectric constant from its mean value. The real and imaginary parts of the frequency of the electromagnetic wave are obtained as functions of the parameters characterizing the randomness of the system by two different approaches, both of which represent improvements of the standard Bourret approximation. In the first approach the dispersion relation has the form $\nu - k^2 = M(k,\nu)$, where $\nu = \varepsilon(\omega^2 / c^2)$ and the self-energy $M(k,\nu)$ is the solution of the nonlinear integral equation

$$M(k,\nu) = \eta^2 \int_{-\infty}^{\infty} \frac{S(q-k)}{\nu - q^2 - M(q,\nu)} dq,$$

where $\eta = \gamma\nu$ and $S(Q)$ is the power spectrum of $\rho(x)$. (In the Bourret approximation the self-energy is absent from the integrand on the right hand side of this equation.) This integral equation is solved numerically, and the complex frequency $\omega(k)$ is determined from the solution. In the second method the integral equation

$$(\nu - k^2)e_k = 1 + \eta \int_{-\infty}^{\infty} \rho_{k-q} e_q dq,$$

where e_k and ρ_k are the Fourier transforms of the electromagnetic field amplitude and $\rho(x)$, respectively, is solved numerically for an ensemble of realizations of $\rho(x)$, and the solution is averaged over this ensemble. The pole of the result occurs at the solution of the equation $\nu - k^2 = M(k,\nu)$. The results obtained by these two methods are compared to each other and to the results obtained from the Bourret approximation.

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Wave Localization in Random Media : a Path-Integral Approach

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In this work we study the propagation and localization of waves in multiple-scattering random media. Instead of exploring the usual diagrammatic technique, we use the Feynman path integral approach [1]. For this purpose we apply the method originally proposed by Fock for the integration of quantum mechanical equations. The method is based on the introduction of an additional pseudotime variable and a transfer to a higher-dimensional space in which the propagation process is described by a generalized parabolic equation similar to the nonstationary Schrodinger equation in quantum mechanics. Next, applying a perturbative technique, we evaluate the statistical moments of the field excited by a point source in a statistically homogeneous Gaussian random medium [2].

The main efforts are directed to the description of the wave localization phenomenon. In particular, we prove that the wave correction for the mean intensity, when being negative, can be interpreted in terms of the localization length. Our results confirm the usual belief that the dimensionality of the system is a crucial parameter. In one-dimensional systems all states are strongly localized, while in three dimensions no indications of a strong (exponential type) localization were observed. We found that in two dimensions there are possibly delocalized states at low frequencies, which can be explained by the fact that, contrary to the quantum mechanical case, the strength of the scattering potential is energy-dependent for classical waves.

In addition, we show that the abilities of a system to produce localization are determined essentially by the correlation function of the inhomogeneities. Apart from regular isotropic Gaussian correlations, some fractal and anisotropic structures are examined. The main conclusion coincides with that of John: The localization in three dimensions is mainly the result of some spatial ordering in the system, rather than of a simple disorder [3]. Though the formula, obtained for the localization length, is valid only for random media with monotonically decreasing continuous spectra, we believe that it may also give a physical insight into both the nature and necessary conditions of wave localization in periodic and near-periodic structures [4].

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Modeling of High-Frequency Propagators in Inhomogeneous Background Random Media

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The problems of remote sensing and location of distant objects in various geophysical environments and the design of modern communication channels sets us the problem of describing wave processes in complex inhomogeneous media in the presence of boundaries and scattering centers. In the high-frequency limit the propagation in spatially inhomogeneous media is intuitively related to the geometrical ray trajectories representing the paths of energy flux transfer. The localization concept around these ray trajectories, and the reflection, refraction, and (or) diffraction of the local plane-wave fields by boundaries, inhomogeneities, and (or) scattering centers has been combined through the geometrical theory of diffraction (GTD) into one of most effective means for analyzing high-frequency wave phenomena in complex deterministic environments. Recently the geometric theory has been extended to account for the statistical character of the problem caused by fluctuations of the medium parameters in order to permit more realistic modeling of propagation channels encountered in practice. This has resulted in the formulation of the Stochastic Geometrical Theory of Diffraction (SGTD) which, similarly to the deterministic GTD, is based on the transport of high-frequency random fields and their statistical measures along geometrical rays in the deterministic background medium. As in the case of deterministic GTD, the main concern is the construction of the propagator relating the values of the field and its statistical measures at some observation plane to their source (actual or virtual) distributions at the initial plane. It is desirable to have a solution which contains in an explicit form information about the random refractive index variation along the propagation path. The starting point is the scalar Helmholtz equation written for the Green's function. Here the lack of the so-called dynamic causality condition due to the elliptic character causes some principal difficulties when one attempts to obtain its solution. This discrepancy can be corrected if one transfers to the equation of a parabolic type. In an inhomogeneous background medium the parabolic approximation can be performed in local coordinates around the curved ray path connecting a source with an arbitrarily located observer in the deterministic background medium. The solution strategy involves the ray-centered coordinates for a typical ray with extraction of the average phase accumulation along that ray.

The advantage of parabolic approach is that the resulting inhomogeneous background parabolic equation can be reduced to the form of the stochastic Schrodinger equation describing movement of a quantum particle in a random potential. It allows us to present the solution for the randomly scattered wave in the form of a Feynman path integral.

Using the path-integral approach various approximate solutions for a high-frequency field propagating in a random medium have been constructed. It has been shown that in order to obtain proper intensity correlation characteristics uncertainty considerations play an important role. To account for the uncertainty in the spatial location and the slope of geometrical ray trajectories we transferred to a higher-dimensional space by defining a paired field product and its spectral transforms known as Wigner and ambiguity functions. Relation of these approximations to the asymptotic multiscale solutions is considered and some possible applications are presented.

Session B07
Thursday, July 16, PM 13:40-17:00
Room G/H
Detection and/or Imaging of Buried Objects

Organisers : Ch. Pichot, S. Caorsi
Chairs : D. Daniels, J. Cashman

Advances in the Ultrawideband Radar Imaging of Buried Mines

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Much attention is being given to the challenge of detecting buried non-metallic mines and National and International programmes are underway to develop more effective sensor systems. Ground probing or surface penetrating radar is one of the technologies that is being actively investigated. This type of radar is commonly an ultrawideband time domain radar. The signal radiated from such a radar takes the form of a wavelet. Such a class of radar signal can be used to gather significant information on the wideband properties of the target, as well as enabling high resolution imaging.

Radar imaging of buried mines is complicated by operation in an environment that is heavily contaminated by clutter from other objects. These may be man-made or natural.

The radar under consideration is an ultrawideband time domain radar producing wavelets of a duration of between 0.5ns to 2ns. The effect, on the system signal to clutter ratio, of optimising the wavelet duration will be examined. This paper considers some of the issues related to operating in a high clutter environment and its impact on radar system performance.

The paper will also address the implications on generic imaging techniques of operating in a lossy dielectric. The effect of the lossy dielectric is to superimpose a spatial windowing filter on the data and this degrades the spatial resolution that is achievable. In turn this limits the types of imaging technique that can be applied to the radar system.

On the Detection of Buried Objects from Inductive Arrays

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A problem of great current interest is the detection and localization of buried landmines from low frequency electromagnetic induction (EMI) measurements. One approach often taken in such problems is to attempt to form an image of the medium under consideration, then subsequently process this image to identify anomalies. In contrast, in this work we aim to extract directly from the data information relevant to the distribution of the targets of interest. In particular, we consider the development of inversion techniques adapted to the processing of data from an EMI array which surveys a region in a progressive manner staring at a known position and moving in a straight line to a final location. The use of such space diversity coupled with advanced signal processing techniques will be shown to improve detection/false alarm performance and localization accuracy relative to a more typical mono-static EMI system.

We begin by developing a forward model relating the observed data directly to the pertinent physical characteristics of the targets of interest including size, shape, orientation, and electromagnetic properties. Our model is obtained using a reciprocity argument and the full three dimensional Maxwell's equations. For simplicity, we restrict our attention to a linearized model obtained under the first Born approximation. The final measurement model expresses the data at the receiver array as a linear combination of physically derived target signature vectors. The vectors carry information about the geometric structure of the buried objects. The weights represent the relative contrast of the objects and the number of vectors is equal to the number of mines in the receiver field of view.

This forward model lends itself particularly well to the analysis of the mine detection/localization problem and to the synthesis of adaptive algorithms for identifying buried mines. We will show how the above model can be used to provide quantitative results on the manner in which detection and false alarm rates and localization accuracy is dependent on the size, orientation, and position of the mines relative to the sensor array. We demonstrate how this analysis and the scattering model can be used as the basis for the synthesis of algorithms for performing mine detection and localization. Because the array is sensitive to mines in a full 3D volume, we can obtain detection and localization information before the array passes directly over or adjacent to the mine. We will discuss algorithms which provide this forward looking information in conjunction with accuracy estimates both of which are progressively refined and updated as the EMI array moves toward the buried object.

Electromagnetic Inversion for Multi-Bistatic Ground Penetrating Radar

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In recent years there has been an increasing interest in use of ground pen-etrating radar (GPR) for detection of buried land mines or other objects located in the ground. To achieve an accurate image it is important that the inversion algorithm be based on an accurate forward model relating the buried objects to the measured electric field. Such model must at least include a model of the antennas and take into account the presence of the
air/soil interface.

In this talk we present an electromagnetic inversion scheme for GPR imaging based on a forward model in which both the antennas and the air/soil interface are explicitly described. The presented forward model is an extension of the model in [1] where the air/soil interface is neglected. Consequently, the present model more accurately describes the physical GPR-configuration, and a better reconstructed image is expected in practice.

The GPR is assumed to be operated in a stepped-frequency mode and the data are collected in a multi-bistatic survey (multiple independent transmitter and receiver antennas). The forward model is based upon the electric dyadic Green's function for a lossy dielectric half space. This dyadic Green's function is constructed from the Green's function for free space using the Fresnel reflection and transmission coefficients. The antennas are modeled by applying Kern's scattering matrix formulation [1]. Also, the dispersion of the soil is accounted for by including a realistic soil model. To analytically calculate the pseudo inverse, the forward model is linearized using the Born approximation. Various regularization schemes are employed to stabilize the analytic inversion. Numerical examples are provided to illustrate the impact of the air/soil interface and the differences among the various regularization schemes.

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Imaging of Buried Objects from Multi-look, Multifrequency Radar Data in the Fourier Domain, Including Antenna Effects

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Radar imaging of buried objects has applications such as mineral exploration and the detection of land mines. Despite much progress, challenges remain. "Imaging" here means the reconstruction of the complex dielectric contrast distribution (i.e. the difference between the dielectric constant of the object and that of the ambient medium). One challenge is that the image from a given set of data is not unique. A second is that the computational load is high and the imaging cannot be done in real-time. A third is the inclusion in the processing of the radiation properties of the antennas.

The non-uniqueness of the problem is due to its non-linearity. Additional data may reduce the indeterminacy, and is obtainable through the use of the transmitting and receiving antennas in multiple combinations of positions, and multiple frequencies. A priori information lies in the following constraints: the contrast calculated must be independent of the antenna geometry, and, versus frequency, its real part is a positive constant and its imaginary part is negative and inversely proportional.

The relation between the data measured and the electrical properties of the object is expressed by an integral equation, whose solution may be found by a means such as the moment method. This usually involves many numerical integrations. Here, the integral equation is spatially Fourier transformed, after which the integrations may be evaluated analytically.

The unknown quantity in the integral equation is the polarisation current density. But the a priori information concerns the contrast. The two are linked, as the current density is proportional to the product of the contrast and the local electric field. We must therefore solve simultaneously for the current density, contrast and field.

The problem is solved iteratively. An initial field is assumed, permitting calculation of initial estimates of the contrast and the current; with the current estimate a new field is calculated. The procedure is repeated until convergence is found. Each iteration requires the solution of a set of linear equations, the coefficients of which must be recalculated, but are available in the form of analytic expressions.

The third challenge mentioned above is the inclusion of the antenna properties. In practice the transmitted field may be the non-planar near field of the antenna, and the data is the terminal voltage of a receiving antenna. These facts are taken into account as follows: the field radiated by the transmitting antenna is expressed as a spectrum of plane waves. The spectral density is simply related to the aperture field, which is easily measurable for any given antenna. By reciprocity, the behaviour of the antenna as a receiver is similar. As most of the processing is performed in the spatial Fourier domain, inclusion of the antenna properties is simple.

Nonlinear Inversion of a Buried Object in TE-scattering

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A method for reconstructing the material properties of a buried bounded inhomogeneous object from measured scattered field data at the surface of the Earth's interface is presented. This work extends the method previously developed for the homogeneous TE-case to the more complicated case of a buried object. In the TE-case, the magnetic field is polarized along the axis of an inhomogeneous cylinder of arbitrary cross-section and the corresponding integral equation contains derivatives of both the background Green's function and the field. The non-linear inversion based upon the modified gradient method can be formulated as an electric field integral equation for the two transversal components of the electric field. Again the integrand is a product of the background Green's function, the contrast and the electric field vector, however in the case of a buried object the background Green's function is the one pertaining to a two-media configuration. The derivatives are operative outside the integral. In this presentation the latter formulation will be taken as point of departure to develop a nonlinear inversion scheme using the modified gradient method.

The presented method for reconstructing the material properties of a bounded inhomogeneous object buried inside a half-space from measured scattered field data at the surface of the Earth is based on earlier work by Kooij and Van den Berg [1]. The present presentation extends the homogeneous TE-case by Kooij and Van den Berg [1] to the more complicated case of an object buried inside a half space. The integral equation is formulated as an electric field integral equation for the two transversal components of the electric field. The derivatives are operative outside the integral operator. These derivatives can efficiently be integrated by using rooftop functions in the discretization procedure. In this presentation the electric field integral equation will be taken as point of departure to develop a nonlinear inversion scheme using the modified gradient method. Numerical results will be shown of buried objects that have conductivity or permittivity contrast. The results are compared to the results obtained in the TM-case.

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An Iterative Scheme for the Reconstruction of Homogeneous Penetrable Objects using a Boundary Integral Method

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The problem of the reconstruction of the shape and of the electromagnetic parameters (ε_r, μ_r, σ) of a homogeneous cylinder is addressed. The initial data is the harmonic electromagnetic field measured in a cross-borehole configuration with dipole antennas. The embedding medium is assumed to be homogeneous with known permittivity and permeability. This extends a previous work devoted to the reconstruction of the shape of a perfectly conducting cylinder [1].

The first step, based on a low frequency approximation, gives an estimation of both the geometrical (i.e. location and area) and electromagnetic parameters. At this step the shape of the scatterer is assumed to be circular. The result is then used in an iterative algorithm based on a rigorous boundary integral method. This algorithm, which can deal with arbitrary profiles, allows us to reconstruct the shape of the scatterer. The cost function is minimized by a conjugate gradient method and the gradient of this function is written in terms of the solution of two reciprocal direct diffraction problems [2] at each step of the iteration.

Numerical experiments have shown that a good convergence requires separating the reconstruction of the profile from the determination of the electromagnetic parameters. Therefore, we alternately optimize one set of parameters, the other being fixed.

In case of high conductivity, since the Green's function decays very rapidly, the associated kernels are approximated by diagonal ones. This allows us to get accurate results with short computation time.

The algorithm has been tested against noisy data obtained by K. Belkebir using a computer code solving the direct diffraction problem with a different method [3].

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Electromagnetic Imaging of Immersed Metallic Structures

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We are concerned herein with electromagnetic imaging of metallic targets immersed in water. The targets are illuminated by time-harmonic sources located in the water, and the images are built up from frequency-diverse data obtained in the reflection-mode. The latter consist of the values of the anomalous field, which results from the interaction between the interrogating wave and the target, collected on a line also located in the water. The geometry is such that sources, targets and receivers are embedded in a stratified medium which consists of two semi-infinite (water and air) domains and such that a 2-D scalar problem is considered in the TM polarization case.

In view of the frequency band (100 MHz < f < 1000 MHz) that is considered, the size of the targets to be imaged is of the same order of magnitude as the penetration depth of the interrogating wave in the water. Hence the modelization of the wave - target interaction can be described as a classical scattering problem where the anomalous field appears to be radiated by Huyghens-type sources located within the target or on its boundary, via an adequate Green's function. The anomalous field is then given by a Lippmann - Schwinger integral formulation.

The inverse problem, i.e. mapping of an unknown contrast function representative of the target from the knowledge of the anomalous field, is led within the framework of inverse scattering. This problem is non-linear and ill-posed. It is dealt with by means of a binary specialization of the nonlinearized Modified Gradient Method, which has proven to be very effective for imaging inhomogeneities embedded in stratified media in aspect limited data configurations for various physical applications [Souriau L, Duchêne B, Lesselier D and Kleinman R E 1996 Modified gradient approach to inverse scattering for binary objects in stratified media *Inverse Problems* **12** 463-481].

The problem is formulated via the solution of the set of coupling and observation integral equations by minimization of a cost function. This cost function is a weighted sum of the residuals of these two equations, the field and the contrast at every point of the test domain being updated separately. The main difficulty comes from the aspect-limited data configuration considered, which means that the data are collected only in the reflection mode and that the sources and receivers cannot be moved all around the target. Although the resulting lack of information is partly compensated for by using frequency-diverse data, an efficient regularization is still needed to overcome the ill-posedness. Infact, a priori information is introduced by considering that the target is homogeneous, hence the contrast function is allowed to take only two values, i.e., after suitable normalization, 1 within the target and 0 elsewhere.

Reconstructions of targets of different shapes will be presented and tests will be made when the attenuation of the surrounding is increased by adding salt to water. Further, we hope to present reconstructions from measured fields obtained from on an experimental setup which is now under developement. This first experimental setup is in fact a reduced scale prototype to assess the feasability of imaging metallic structures immersed in the sea.

On the Characterization of a Conductive Body in a Conductive Earth Using Low-Frequency Asymptotic Analyses

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Characterization of masses buried inside the Earth in surface-to-borehole and borehole-to-borehole measurement configurations at induction frequencies greatly benefits from today's availability of miniature 3-component electromagnetic probes, but correct interpretation of such data requires a sound understanding of the interaction between the probed masses and the probing sources. Here, we will focus onto the case of a simple homogeneous 3-D conductive body (sphere, spheroid, ellipsoid) located in a homogeneous conductive space, illuminated by a small electric loop (a magnetic dipole), and probed from exterior time-harmonic magnetic fields (both source and receivers are close to the body with respect to the skin depth in the embedding).

Though this seems simple a problem in terms of geometry with respect to typical induction prospecting geometries, it already corresponds with practical cases when the interaction with the earth surface is neglected. And in terms of electromagnetics, localized vector sources, near-field phenomena, frequency dependence of the interaction, and conductive environments are in contrast with the plane-wave, far-field, zero-order approximate expansion, vacuum embedding hypotheses actually made in the realm of the low-frequency theory. As for the limited measurement space, it means that only partial identification can be expected, and at a first stage building up an equivalent source and, at the next stage, an equivalent body, is already quite satisfactory an achievement. The presentation itself will develop as follows.

First, one will consider the magnetic fields associated with a spherical body. We will exemplify that they can be equated to those radiated by a set of equivalent dipoles, once shown that experimental data acquired in several earth configurations can be fairly reproduced likewise. This will be related to already known approximated formulations, and to a novel low-frequency dyadic field expansion of the electromagnetic field whose coefficients come from solving an elaborated succession of potential problems. Possible retrieval of the body parameters themselves will also be discussed briefly.

Second one will consider what happens when the body is a tri-axial ellipsoid. Though the dyadic expansion above may be generalized to such a case, it appears easier to employ first the localized nonlinear approximation —for which the inner fields result from the product of a depolarization dyad (proper to the body) by the background field. The low-frequency expansion of the dyad will be exhibited in closed-form, the starting point being the series of the Green's function in the appropriate ellipsoidal system of coordinates. (Careful reduction yields its expression for a prolate or an oblate spheroid, and for the sphere —presently the only known 3-D case.) Then, it will be shown that such results enable fair calculations of the scattered field, and may be used for the characterization of the geometrical and electric parameters of an equivalent ellipsoidal body.

Underground Tomogram from In-Situ Data Measured in the Cross-Borehole Configuration

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Detection of isolated target such as deep underground tunnel may be possible by the cross-borehole measurements. In-situ permittivities and conductivities of the underground medium may be obtained by three borehole measurements; one for the transmitting (source) short dipole antenna and the others for the receiving antenna picking up the scattered fields at two different distances. By taking the division of these two fields, one may obtain the permittivity and the conductivity from the ratio of the amplitudes and the difference of the phases, respectively.

Multi-frequency averaging of these permittivities and conductivities smooths out not only the dispersive characteristics but also the rapid fluctuations across the planar discontinuities such as cracks and faults. It is shown by the three dimensional simulations that cracks and faults may be identified by the back projection of the multi-frequency averaged permittivities and conductivities. The isolated targets such as the air tunnel, however, produces fluctuating interference fringes of permittivities and conductivities near the target, even with the multi-frequency averaging. After identifying the isolated target from the interference fringes and by defining the region of reconstruction, one may reconstruct the isolated target by using the iterative inversion method. The three dimensional numerical simulations shows that the successful reconstution of the air tunnel is possible.

The tomogram of permittivities and conductivities distribution of the cross section including the air tunnel are obtained from the in-situ data measured by Ra-Geovis, the continuous electromagnetic wave underground radar, by using the multi-frequency averaging and the backprojection. The measured fields are from 10MHz to 60Mhz with 2MHz step and 201 measurement points along the borehole with viewing angles of -45, -30, 0, 30, 45 degrees.

Session C07
Thursday, July 16, PM 13:40-17:00
Room I
Advances Techniques in TLM Field Computation

Organiser : C. Christopoulos
Chairs : C. Christopoulos, M. Ney

A Modification of TLM Method for Dispersive Media, Suitable for Experimental Data.

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The TLM method has been modified for the inclusion of frequency-dispersive behavior. This is achieved by a source technique that combines classical HSCN node and voltage sources, accounting for the response of the media due to previous values of the field.

The basis of the technique is as follows: firstly the Maxwell equations are discretized on a space-time mesh, with inclusion of the dispersive behavior through the relationship between the field vectors of the media. The convolution can be performed in either recursive or non-recursive way, depending on the frequency characteristics of the media to be considered.

Afterwards, the equations for the HSCN node, with three voltage sources through gates 16, 17 and 18 are compared with the previous discretized Maxwell equations. This comparison gives the values of the characteristic admittance and impedance of the lines and the permittivity stubs, giving then the algorithm for updating the sources each time iteration. The algorithm can be performed recursively or non-recursively, depending on the convolution.

The technique has been applied successfully, with classical models of dispersive behavior (i.e. Debye, Lorentz, etc.…), by comparing the theoretical and numerical results for the reflection coefficient (magnitude and phase) at the interface of non-dispersive/dispersive media.

As long as the convolution can be performed not only with theoretical values, but with numerical ones, the method is suitable for use with experimental data, either in the time-domain or in the frequency-domain (in the second case, an inverse discrete Fourier transform has to be done). In this work we will apply this technique to different experimental data, obtained with time domain reflectometry, and for different dielectrics.

Application of the Propagator Approach to the modelling of dispersive media in TLM

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For time domain modelling of dispersive media the material properties have to be modelled nonlocally with respect to time. In this paper we present an extension of the TLM method for time domain modelling of dispersive structures. The work is based on the operator formulation of the TLM method introduced in [1]. For the modelling of dispersive media various models like the Debye, Lorentz or Cole-Cole model have been developped [2]. Utilizing the propagator approach developped in [3], a consistent time domain description of dispersive media is achieved. Furthermore, canonical stability criteria for the TLM process are provided, which yield the time step. To solve Maxwell's equations in connection with the time domain description according to the Debye model, we adapt the discrete propagator approach introduced by Hein [4].

In time domain, the polarization given by the Debye model may be described by a first order differential equation. A special solution of this differential equation is given by a convolution integral. This convolution integral is evaluated analytically for a step function of time of the applied external electric field. After discretization, this leads to recursive relations for updating an additional vector. Hence, the original TLM process is „perturbed" by the updating of this vector and a stability analysis yielding the time step has to be performed.

The numerical results have shown, that the approach is valid for virtually every value of static permittivity, which was tested up to an $\varepsilon \approx 100$. An infinite parallel plate waveguide with a free space - dielectric interface was modelled. The reflection coefficient was calculated via Gaussian pulse excitation and compared with the analytical solution. The accuracy of the approach is excellent, the relative error in magnitude is of the order of 0.001% and the relative phase error is strongly dependent upon discretization.

This work has been sponsored by an Ernst-von-Siemens scholarship.

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Investigation on the Dispersion of 3D-TLM Condensed Nodes : Comparison with the FDTD Yee's Scheme

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Both, the FDTD method using the Yee's cell and the TLM method using condensed nodes are numerical schemes of order two in space and time. However, they have different memory requirements and numerical dispersion characteristics. The objective of this work is to compare the velocity and resolution error produced by these methods in the case of inhomogeneous cavities, using variable parallelepipedic cells (structured mesh). Hence, the comparison will be made under realistic and practical situations. A pioneering work on this subject was presented by Celuch-Marcysiak and Gwarek [1]. They show the comparison between the dispersion error produced by the TLM Symmetrical Condensed Node (SCN) and the FDTD in an inhomogeneous medium but with uniform cubic mesh. Recently, Trenckic et *al.* [2] extended the dispersion analysis to other TLM condensed nodes such as the Hybrid (HSCN) and the Super SCN (SSCN). Comparison was made between the various TLM schemes in the case of an homogenous cavity. However, no comparison was made with the FDTD or/and inhomogenous cases.

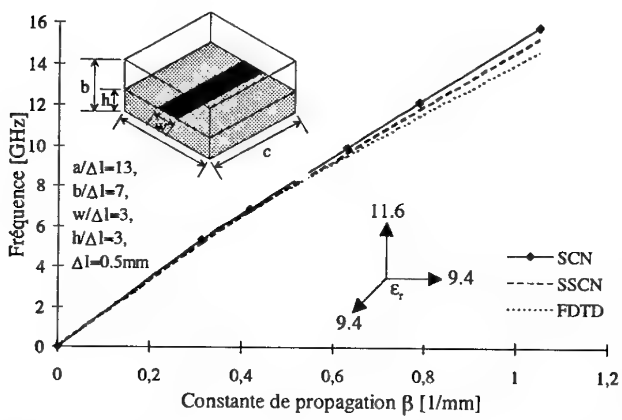

Figure 1: Dispersion diagram of a shielded microstrip line with anisotropic substrate with ε_{xx}=9.4 =ε_{zz} and ε_{yy}=11.6. (FDTD after [3]).

Investigations showed that in the case of inhomogeneous media, both the FDTD and the SCN tends to produce the same accuracy. However, other factors such as the misalignment between dielectric interfaces and electric walls may play a significant role. Also, if the SSCN has a minimum memory requirement among the TLM schemes, the dispersion is higher. These observations are illustrated in fig. 1 where identical cell size and time-step were used. The SCN gives the results which are the closest to the benchmark solution (very fine mesh). Other factors such that abrupt transition of constitutive parameters (interface) or the presence of metallic edges which require irregular mesh may influence the precision. The results will shed some light about the memory and CPU-time requirement for a given accuracy and give some objective comparison between the FDTD and the various schemes of the TLM condensed nodes.

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Recent Enhancements to TLM for Industrial Use

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This paper describes novel techniques derived to enhance capabilities of the three-dimensional transmission-line matrix (TLM) method in modelling arbitrary electromagnetics problems encountered in the industrial environnements. The enhancements are mainly oriented to allow modelling of smaller features in an otherwise large modelling space. We describe here a new multigrid interface, an improved wire node as well as an integrated multiconductor model.

In the TLM method, the modelled space is usually divided into a large number of cuboid cells on an orthogonal grid or mesh. In many problems which require modelling of small details in a large modelling space it is desirable to allow connection of a fine mesh with small cells to a coarse mesh of large cells, which is usually referred to as multigridding. In the multigrid scheme presented here, the same time step is used on both the coarse and fine meshes while the connection is established using passive electrical circuits inherent to TLM (rather than using an averaging process). The electrical connection is established using ideal transformers so that the whole proces is lossless.

Modelling of conductive cables coupling with the electromagnetic field presents another common problem for time-domain modelling techniques because of the problem topology. Here, special TLM wire nodes are presented which allow modelling of thin wire structures, with a diameter much smaller than the cell size. In addition to the usual link lines and stubs, these TLM nodes can contain other circuits which are used to model straight wire segments, wire bends and wire junctions. Finally, a new multiconductor model has been introduced allowing for an integrated modelling of arbitrary cable structures.

Results of modelling microwave structures using these advanced techniques are prensented to support the theoretical findings. All these improvements are implemented into a 3D TLM software package called Micro-Stripes and is commercially availble.

New TLM Nodes for Modelling Sharp Zones in Resonant Situations

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The versatility of the Transmission Line Modelling (TLM) method for solving physical situations involving wave propagation, electromagnetic or not, has generated and enormous increase in the interest for developing modifications to the standard formulation in order to adapt the method to the treatment of new and challenging problems. One of the most critical points to be accounted for in electromagnetic calculations is the appropriated modelling of regions where a rapid variation of the electromagnetic field is expected. These points are usually connected to the existence of sharp regions, such as thin conducting parts, corners and edges. The standard simulation of this type of problems uses a mesh of symmetrical condensed nodes with lines short-circuited halfway between nodes. In a great number of cases, results obtained in this way are fairly good; however, when dealing with resonant problems, a certain shift in resonant frequencies is observed unless a very fine mesh is used. This shift has already been observed in situations involving wires and thin conducting planes, and it seems to be connected with the rapid field variation in the vicinity of this region and the indirect path that individual pulses must take around sharp bends. Initial efforts to solve these problems dealt with the modification of the medium near these regions in order to increase the speed of pulses around them and so diminish the effect of the indirect path. The other solution available in the literature consists of the development of new nodes to model the existence of a conducting plate inside the node. This later solution provides good results with a relatively coarse mesh since the problem of the indirect path is avoided, but also because, in this solution, the boundary condition involves not only two lines between nodes, but also takes into account all the lines in the node. As mentioned above, a number of special nodes are available in the literature but the simulation of arbitrary conducting geometries still the development of new nodes. The aim of this paper is to develop the new nodes needed for the modelling of arbitrary geometries, especially those concerned with resonant situations. The good behaviour of these nodes is evidenced by their application to several problems in which the elimination of the above-mentioned frequency shift is demonstrated.

Simulation of Microwave Circuits Using TLM

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The design of high-performance and topologically very complex microwave circuits requires a good understanding of the behaviour of microwave circuits discontinuities. Lumped circuits have been used in the past to describe the impact of discontinuities but these techniques cannot account fully for the behaviour of three-dimensional electromagnetic fields especially when several discontinuities are in close proximity and therefore the associated higher order modes interact with each other. In such cases whole system modelling using a three-dimensional field code is necessary. The size of such computation is considerable and very often a frequency-domain code is employed. However, it will be shown in the paper that time-domain electromagnetic codes can be used successfully to tackle such problems. The advantage of solution in the time domain is that complete information is obtained from a single simulation over a wide frequency range and there is scope for animation and interpretation of the evolution of fields around a discontinuity and in the whole circuit. Results in the frequency domain may be obtained from a Fourier transform of the time domain data and presented in the usual way, e.g. in the form of S-parameters.

This approach is illustrated by applying the Transmission-Line Modelling (TLM) method to study the behaviour of a 11-th order high-pass microwave filter with generalised Chebyshev characteristic. The filter was designed for 4 GHz cut-off frequency and realised using suspended substrate stripline technology. The modelling philosophy will be explained and the results will be compared with experimental ones. An assessment of the sources of error in such simulations will be wade such as numerical dispersion, edge effects and open-boundary reflections.

TLM Analysis of CPW Bend used to Provide a Circular Polarisation

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The applications of coplanar waveguide are various and the popularity of these kind of transmission line is increasing due to their many advantages as wider bandwidth in the case of microstrip antennas excitation, smaller mutual coupling between adjacent lines, and easy integration of active devices. A lot of studies have been done on this type of waveguide used to provide linear polarisation [1-3] but the first design of a circularly polarised antenna using CPW fed was presented few time ago [4]. The antenna described in [4] was based on the excitation by the line of two square-slot-loops antennas set asymmetrically to radiate identical polarised waves. The structure proposed (fig. 1) in this paper is an easy-to-design solution with a single square patch antenna fed by a CPW. The circular polarisation is provided by the electrical delay introduced by a bend in the CPW line under the square radiating patch. The phase shift created between the propagating fields in the slots allows to excite the radiating element with two orthogonal modes of equal amplitude and a differential phase shift of +/- 90°. The CPW line after the patch is short ended and acts as a matching stub. Experimentally, a good matching is obtained for the input impedance in the same frequency band where we obtain a good axial ratio of circular polarisation (4.92-5 GHz). The TLM approach is used to determine the propagation of electric and magnetic fields in the CPW line, the input impedance and the near and far radiated fields by the structure. The validity of the TLM analysis is established by comparing with experimental results. The original use of the bend allows to think to serial fed excitation of microstrip antenna arrays circularly polarised.

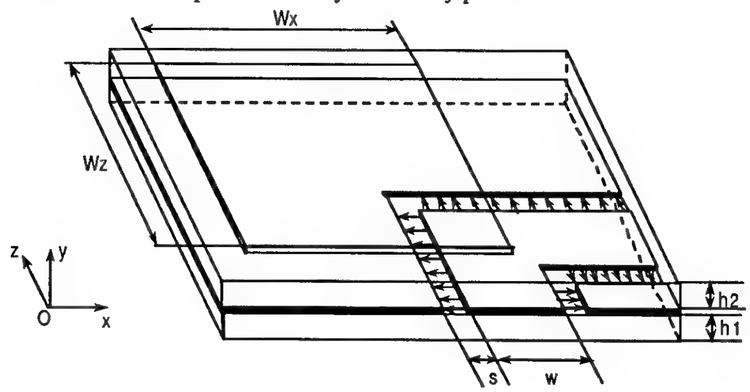

Figure 1

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Field Theoretical Derivation of Lumped Element Equivalent Circuits or Multichip Module (MCM) Chip-Connections

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With increasing operating frequencies scattering at transmission-line discontinuities along interconnecting paths is becoming more and more a limiting factor in modern circuit design. To overcome these restrictions accurate full-wave analysis based modeling techniques applied to distributed circuit parts have to be combined with general purpose circuit simulators used for non-linear circuit design. A possible solution is to directly integrate lumped elements into full-wave analysis [1], [2], but it is often advantageous to separate EM and network simulation. Combining all different modeling results directly is shown in [3]. The most flexible and most common one is to use a lumped element equivalent circuits model representing a specific distributed circuit element. Though these models are widely used, only a few papers found in literature address the problem of a systematic method for the generation of lumped element equivalent circuits. In [4] a straight forward parameter extraction technique for the linear, reciprocal, lossless case is given. But usually empirical methods are used to find an appropriate network structure representing a given transmission characteristic.

We present a method for computer aided generation of lumped element equivalent circuits for linear reciprocal distributed microwave circuits. The method is based on a field theoretical analysis of the distributed multiport circuit by the time domain Transmission Line Matrix (TLM) method. The topology as well as the parameters of the lumped element equivalent circuit are generated after specifying an arbitrary but finite interval of frequencies. These models provide an accurate description of the distributed circuit within this frequency range and exhibit a considerably reduced complexity.

Starting with a three-dimensional electromagnetic full-wave analysis of a distributed multiport we obtain the impulse response functions for reflection and transmission between the ports. For this we use the time domain TLM scheme with Symmetrical Condensed Nodes [5] and make use of existing extensions like an irregularly spaced mesh. Based on a canonical representation of the admittance matrix Y(p) of a linear reciprocal multiport an equivalent circuit model may be specified directly. The admittance matrix may be represented by

$$Y(p) = A^{(0)} + \sum_{n=1}^{N}\left(\frac{A_0^{(n)}}{p-\alpha_n} + \frac{A_0^{(n)*}}{p-\alpha_n^*}\right)\cdot A^{(n)} + A^{(\infty)}p \quad (1)$$

In order to describe passive circuits the parameter space of (1) has to be limited. Within these restrictions a valid parameter set of (1) approximating results obtained from TLM simulation has to be found. Doing this in a systematic way we split the process of model generation into subsequent steps. In contrast to system identification techniques like Prony's Method the extraction of admittance function pole locations a_n is separated from the determination pole amplitudes and phases. This task is performed afterwards with fixed pole locations.

The method has been applied to several multichip module interconnecting structures like multichip module chip-connections. A full-wave analysis of these discontinuities including varying substrate materials, glue fillings and three dimensional conductor structures requires for a three dimensional field modeling. Therefore, all pulse response functions contributing complete descriptions of the distributed circuits had been calculated by three dimensional TLM-simulation and equivalent lumped element models were generated. Results for different structures including lumped element equivalent circuits will be presented at the conference.

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Comparison of TLM-GSCN and FD-TD Dispersion Characteristics

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I recent years, the transmission-line matrix (TLM) modelling and finite-difference time-domain (FD-TD) methods have established themselves as primary tools in the electromagnetic field analysis of arbitrary high-frequncy structures requiring a wide band response. Tha key difference which distinguishes the TLM symmetrical condensed node (SCN) scheme from the FD-TD is its non-staggered computational mesh where all field components can be evaluated at a single point of space. This topological advantage also facilitates an easy modelling of material discountinuities and boundaries in SCN-Tlm. When operating in its stability limit, that is, when a homogeneous medium is being modelled on a uniform mesh, the SCN-TLM scheme exhibits a smaller dispersion error than the FC-TD. However, the sipersion characteristics of the ordinary stub-loaded TLM-SCN scheme deteriorate sharply when modelling inhomogeneous media and using non-uniformly graded mesh, i.e., when operating on a time-step smaller than the maximum allowed.

In addition to the ordinary SCN-TLM scheme, where the impedance of the link lines is kept equal to that of the background medium and open - and short - circuit stubs are used to model nonbackground materials and mesh grading, other more advancrd TLM schemes were derived. They are more flexible in terms they use different link line impedances, so they can reduce memory requirements (by using only one type of stubs or not using them et all) andallow for a higer time-step for graded meshes. A thorough study revealed that these schemes exhibit different dispersion behaviour, depending on how the excess of material and geometrical properties is being modelled (by adding stubs or changing the impedance of link lines). Since the combination of link and stubs in a TLM node can be achieved in many different mays, a scope for optimization of dispersion properties was noticed. To allow for this, it became necessary to establish a node with a general configuration of link lines and stubs, which was recently completed through the definition of so-called general symmetrical condensed node (GSCN).

In this paper, the dispersion properties of several TLM schemes based on the GSCNare systematically compared with that of the FD-TD scheme. The effect of the time step on the dispersion was studied by plotting the propagation error for different ratios of $r = \Delta t / \Delta t_{\max}$. The attention is also placed on the numerical anisotropy, i.e., the propagation error is studied on the diagonal plane $X = Y$ as a function of an angle formed by the propagation vector and the Z axis. In this way a number of propagation modes of the from [m, m, n] can be studied, including all modes of the primary interest, such as [0, 0, 1], [1, 1, 1] and [1, 1, 0]. It is shown that, altrough traditional TLM nodes exhibit worse dispersion properties and a higher error that the FD-TD, it is possible to derive a class of nodes, as adaptable SCN (ASCN), with superior dispersion characteristics and an error smaller that of the FD-TD scheme. It is also shown that the hybrid SCN (HSCN), altrough suffering from polarization-dependent dispersion, is more accurate than the FD-TD and can be consideredc as a good memory-efficient alternative to the ASCN.

Session D07
Thursday, July 16, PM 13:40-16:40
Room 120
Hydrid Methods

Chairs : T. Sarkar, T. Weiland

Hybrid FDTD-FETD Method for 3D Antenna Modeling

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During the last decade, the Finite Difference Time Domain method (FDTD) has become a prevalent method for solving various electromagnetic problems. This method presents a lot of attractive advantages: easy programming, low computational complexity, rapidity and performant Absorbing Boundary Conditions (Perfectly Matched-Layer ABC). But one major disadvantage of the FDTD is the use of a structured (regular rectangular) grid.

On the other hand, the Finite Element Time Domain method (FETD) offers some benefits. The most obvious one is that one can resorts to an unstructured grid, providing a superior versatility in modeling complex geometries. Furthermore, the Faedo-Galerkin procedure, used for the development of the weak formulation, provides a very natural way for handling field and flux continuity conditions at material interfaces, thus further enhancing modeling accuracy.

For exploiting the advantages of each method, it seems interesting to couple both methods: confining the FETD in the complex region and using the FDTD in the exterior (regular region) with ABC. Thus, the hybrid method can offer a better computational efficiency since it preserves both advantages of FDTD and FETD. Moreover, the implementation of the hybrid method on a parallel computer allows for further decreasing in computer time.

This hybrid method is applied to solve antenna problems for three dimensional arbitrary structures like dielectric resonator, microstrip and stripline antennas. Numerical results are compared with ones obtained with conventional FETD and FDTD in order to demonstrate the performance of the hybrid method.

Accurate and Fast Design of Waveguide Components by Hybrid Mode-Matching/FE Buildings Blocks in a Powerful CAD Tool

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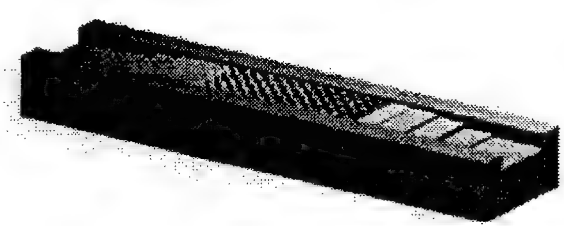
MODERN communication systems, such as satellite or high-capacity microwave radio relay links, require the accurate design of high performance waveguide components for many applications. Although numerical (EM) 3D analysis techniques, such as the finite element or finite difference approach, are commercially available for a rather long time meanwhile, the challenge is to go beyond the traditional use of EM simulators for mere validation and analysis purposes. With the steadily growing requirements and increased specifications, it is to develop and utilize EM building blocks which are fast enough to allow the direct application of optimizers and convenient CAD tools.

In this paper, fast hybrid mode-matching/finite-element wavequide building blocks are described for the optimization oriented use in powerful circuit CAD tools and the automated design of advanced waveguide components which include structures of more general shape. For structures which require a high number of eigenmodes to be considered, like ridge waveguide filters including air gaps, the 2D FE method is applied because of its high efficiency. In contrast to other methods, no search procedure for the detection of eigenvalues is necessary where the resulting computation time can be rather long, especially if optimization routines are used. The initial mesh for the two-dimensional FEM solution of the Helmholtz equation for the sections with arbitrary geometry is generated by th Delaunay triangulation ; the mesh can locally br refined and optionally be smoothed. The generalized matrix eigenvalue problem is reduced to tridiagonal form by the Lanczos procedure, with application of a shift and invert technique to accelerate convergence. Full Gram-Schmidt type re-orthogonalization guarantees the orthogonality of even higer-order multiple degenerate modes. The system of equations arising in each Lanczos iteration step is solved by sparse matrix Cholesky decomposition using the minimum degree algorithm.

In addition to the typical combination of homogeneous waveguide sections by the generalized scattering or admittance matrix combination techniques, a fast block-LU-decomposition method is utilized. The block-LU-decomposition technique solves the whole set of equations for the normalized modal voltages u and currents i directly and yields immediately u_i, i_i at each waveguide section i. To demonstrate the efficiency of the method, waffle-iron filters and septum polarizers (Fig. 1) are designed achieving high performance components without the need for additional tuning elements. The theory is verified by excellent agreement with measurements.



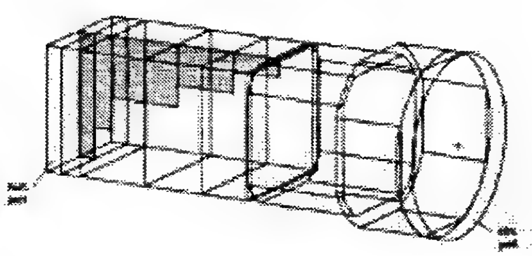


Figure 1 : EM theory based CAD examples : Waffle-iron filter and Spectum Polarizer

New Time Domain Integral Equation Approach for Hybrid Methods

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These last years, an important development of numerical approaches for dealing with electromagnetic diffraction problems can be noted. The increasing of such an intensive computation is due to the development of the computer capability. The challenge is to give models which are more and more representative of complex structures, but each theoretical approach has its drawbacks and its advantages. The typical example is the wire networks modeling which is very limited with some approaches (ex : the FDTD method only allows to take into account wires flowing along the cartesian axis) [1]. Consequently, a way to overcome the drawbacks of an approach is to make an hybridation with another method which is more suited for modeling some parts of the structures.

In this paper, we will introduce a new time domain integral equation approach which is well adapted to be coupled with other codes such as FDTD. This approach is a vectorial extension of the Liu and Mei formalism [2]. It has been applied for two hybridations :

- When considering long transmission lines, we have demonstrated that if numerous bends are present on this line the usual Transmission Line (TL) method gives erroneous results [3,4]. This phenomenon is due to radiation neglecting at the bend level. In this paper the idea is to rewrite the integral equation method as a generalized TL approach with extra terms for taking into account coupling between segments. In such a formalism, it is possible to change the number of coupled segments at every point of the line : for straight parts, the coupling of an element on itself is sufficient (ie TL method) ; at the bend location, interaction sphere allows to determine the number of segments to take into account.

- The usual Finite Difference method is not able to correctly model thin wires in any direction. Usually, the wires have to follow one of the axis of the cartesian coordinates. So, to improve the method, an integral equation has been introduced in FDTD codes. One of the advantage is that it is possible to consider oblique wires connected to a surfacic or volumic object.

Conclusion

In this paper, a versatile integral equation for thin wires has been introduced that allows the increasing possibility of usual codes ; two applications have been investigated. We think that our approach can be extended for some others applications.

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Computation of 3D Anisotropic Scatterers by Several Hybrid FEM/BEM Methods

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The electromagnetic scattering from composite anisotropic dielectric and conducting structures is modeled by a hybrid partial differential equation / integral equation method. We use the edge elements discretization for both equations and coupling.

The partial differential equations called MFVE (magnetic field volumic equation) and EFVE (electric field volumic equations) are discretized by using the Hcurl Nedelec element on tetrahedra (one degree of freedom by edge). These formulations are specially well adapted to approximate the electromagnetic field in heterogeneous iso/anisotropic media.

The integral equations called EFIE (electric field integral equation) and MFIE (magnetic field integral equation) use edge elements based on Rao-Glisson discretisation on triangles. These formulations are applied for the computation of the electromagnetic field in homogeneous isotropic media.

Several formulations of the coupling are proposed here in the general CEM solvers HEM3D developped at ONERA and SPECTRE at Dassault Aviation : HEM3D94 combined MFVE/EFIE using a mixed elements formulation (linear piecewise elements to approximate the electromagnetic field on tetrahedrons and triangles) : SPECTRE94 combined MFIE/EFIE with edge elements, HEM3D97 and SPECTRE97a combined EFVE/EFIE with edge elements, SPECTRE97b combined MFIE/MFVE with edge elements.

The solution of HEM3D formulations is made by using an iterative solver : Multi Generalized Congugate Residual. This solver is well adapted to solve a partially sparse complex matrix (could be stored in core or computed at each iteration) with several right hand sides. Parallelization of HEM3D is done on PARAGON and CRAY.

The solution of SPECTRE97 formulations is made by using direct solvers for sparse matrix (issued from volumic equations) and dense matrices (from integral equations and coupling). These matrices are stored out of core and the parallelization is done on a SP2. The volumic equations in SPECTRE94 are solved with a iterative Quasi Minimal Residual solver or Block Quasi Minimal Residual solvers (Freund al) but these solversare not efficient enough when many right hand sides are required.

Several tests on differents geometries are proposed in order to have a good comparison of all these approaches : dielectric plates, anisotropic spheres and an iso/anisotropic prismatic scatterer. We obtain the best results with the edge formulations when the geometry of the scatterers are not smooth enough (with edges, corners or tips).

Analysis of High Frequency Electron Devices using a Hybrid FE/FD-TD Technique

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High frequency electron devices have been conventionally simulated by separately considering electromagnetic (EM) wave propagation and charge transport phenomena. Recently, first attempts to fully consider the coupling between these two aspects of the device physics have been proposed [1]. For instance, the Finite Difference Time Domain (FDTD) technique has been used in [2] while a mode-matching technique has been adopted in [3]. Both works suffer of some limitations: the former presents the well-known difficulties encountered in FDTD when modeling complex structures (curved boundaries), whereas the latter considers a simplified device model, accurate only in steady-state conditions.

A hybrid Finite Element/Finite Difference Time Domain (FE/FD-TD) procedure is applied [4] in this work, allowing us to overcome the restrictions of previous approaches. A careful analysis of the device physics shows that two separate regions can be identified where the internal device dynamics is governed by mechanisms of different kind. The first region represents the active area of the device, where charge transport and control phenomena occur, and will be referred to as the intrinsic device. The other region provides interconnections between the intrinsic device and each external terminal, and will be referred to as the extrinsic device. The presence of dielectric stratification must be accounted for, in modeling this second zone.

The intrinsic device is analyzed by means of a conventional FDTD scheme [2], while the passive structure is analyzed by means of a fully stable formulation of the FE-TD. The FE method [4] features greater flexibility and versatility than the FDTD technique in modeling arbitrarily shaped regions, such as those encountered in GaAs FETs devices (trapezoidal terminals, curved doped regions). The interlacing between the EM fields in the structured and unstructured grids is performed according to the scheme presented in [4]. This results in a very flexible technique, able to take into account the interaction between charge transport mechanisms and EM fields, considering, at the same time, the actual geometry of the device with no 'staircasing' error.

EM field distributions at specific sections of the transistor have been determined as a function of the channel conductivity and the gate recession. Numerical results will be shown to describe the behavior of the device for different geometrical shapes and dimensions.

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Improved FE-FCT Method for the Solution of Gas Discharge Problems

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An improved finite element-flux corrected transport (FE-FCT) method for the numerical solution of hydrodynamic conservation equations is described. This is based on the method developed by Lohner and his collaborators to solve conservation equations in fluid mechanics, and its application is extended to gas discharge problems. The method employs the two-step Lax-Wendroff scheme as the high-order scheme and diffusion is added to transform it to a low order scheme for use in the FCT algorithm. The diffusion term is added by subtracting the lumped mass matrix from the consistent mass matrix. A variable diffusion coefficient is introduced; it is assumed to be constant in each element and is shown to transform the high-order solution to an upwind scheme which has minimal diffusion but ensures positive results; a critical requirement for the performance of the FCT algorithm. The upwind scheme is not used as the low order scheme despite the fact that it contains the optimal diffusion because this becomes very complex in finite elements (it requires operator splitting) and it would make the method very inefficient and computationally expensive. Instead the diffusion coefficient inherent in the upwind scheme is used which still gives optimal diffusion for the FCT algorithm. Thus the method gives optimal performance but also maintains its simplicity and computational efficiency of Lohner's method as upwinding is avoided.

This method is applied to positive streamer calculations. Theoretical results are presented for the formation of breakdown streamers which bridge a 1mm gap between a positive 50 micro m diameter hyperboloid point and a plane, when a voltage of 3kV is applied. Preliminary experimental results show that for such gaps streamers only form when 2.5 to 3kV are applied, and that the streamers which are formed, bridge the gap as in the theoretical calculations. The results generated with the new improved FE-FCT code are compared with a pre-existing finite difference code, and they are shown to be almost identical. The FE-FCT method nevertheless offers the advantage that unstructured grids can be used to describe arbitrarily shaped electrodes.

Solution of Nonlinear Coupled Electromagnetic-Thermal Problems Using the Finite Integration Method

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The calculation of coupled electromagnetic and thermal fields is of increasing importance for many technical applications. Examples are not only induction and microwave heating systems, where the heating of materials is the goal, but also many practical cases, where material heating by electromagnetic energy absorption cannot be avoided. Even if one is not interested in the temperature distribution, the coupled problem has to be solved whenever the temperature dependence of the electromagnetic material properties is not negligible.

Problems of this type can be described by the following system of nonlinear differential equations :

$$\mathrm{rot}\,\vec{E}\,(\vec{r},t) = -\frac{\partial}{\partial t}\left[\mu(\vec{r},T)\vec{H}(\vec{r},t)\right]$$

$$\mathrm{rot}\,\vec{H}\,(\vec{r},t) = -\frac{\partial}{\partial t}\left[\varepsilon(\vec{r},T)\,\vec{E}(\vec{r},t)\right] + k(\vec{r},T)\,\vec{E}(\vec{r},t)$$

$$\mathrm{div}[\varepsilon(\vec{r},T)\,\vec{E}(\vec{r},t)] = \rho$$

$$\mathrm{div}[\mu(\vec{r},T)\,\vec{H}(\vec{r},t)] = 0$$

$$\rho(\vec{r},T)\,c(\vec{r},T)\,\frac{\partial T(\vec{r},T)}{\partial t} = \mathrm{div}\left[k(\vec{r},T).\mathrm{grad}T(\vec{r},t)\right] + k(\vec{r},T)\left|\vec{E}(\vec{r},t)\right|^2$$

Analytical solutions of this system are practically impossible, the system has to be solved numerically. For this task we use the so called "Finite Integration Method".

The Finite Integration Method (FIM) is a proven consistent discretization method for the computation of electromagnetic fields. It transforms Maxwell's equations in their integral form directly into matrix equations in a grid space with two staggered grids. One of the outstanding properties of this so-called Maxwell Grid Equations (MGE) is that properties of the analytical solutions have their analogues in the grid space. In this paper we present the application of the FI-Method to the transient heat transfer equation and the coupling to Maxwell's Grid Equation. After a short introduction to the basics of the FI-Method and the MGE we apply the FI-Method to the transient heat transfer equation. This yields a matrix equation consisting of the same operator matrices as used in MGE. For the time derivative we discuss two approximations which lead to an explicit and an implicit algorithm, respectively. If the temperature dependence of the electromagnetic material properties is negligible, we can solve the coupled problem in two steps; first we solve the electromagnetic problem, then we solve the heat transfer equation using the losses from the electromagnetic solution as excitation. In general this assumption is not true and we have to solve the two problems simultaneously. In our computation this coupling is taken into account by automatically switching between the two solver algorithms during the time integration of the heat transfer equation. Finally we present an example for a nonlinear coupled electromagnetic-thermal problem.

An Hybrid Formulation Combining FDTD and TDPO

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The Finite Difference Time Domain (FDTD) technique [1] has been proven to be particularly well suited to study microwave circuits and antennas. However, its main limitation results from the increase in both computation time and memory storage when the studied structures become larger. In spite of the constant improvements brought to the method itself as well as in the computers power, the maximal realistic computation volume is still restricted to a few wavelengths in each direction. On the other hand, asymptotic approaches, such as the Physical Optics [2] are generally used to account for very large scatterers but are not valid to study small radiating structures.

Recently, several examples [3], [4] have been reported, in which a rigorous electromagnetic method was combined with an asymptotic approach in order to study small radiating sources close to large scatterers. So called hybrid methods have been demonstrated as able to account for the environment of the antenna while maintaining the needed accuracy in the description of the antenna itself.

This paper proposes a new hybrid technique that combines FDTD with the Time Domain Physical Optics (TDPO). As the whole approach is performed in time domain, it is expected to be suitable for broad band analysis. Moreover, the Physical Optics allows the closeness between the small element and the large scatterer contrary to Geometrical Optics where the source is supposed to be far from the obstacle. Their support may even be the same. In the presentation, both methods as well as the way they are connected together will be described in more detail. Then the hybrid method will be applied to study the radiation of a wire antenna in presence of a large conducting plan. A comparison between the new technique and the classical FDTD method will be provided in order to discuss the computation efficiency of the new approach.

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Session E10
Thursday, July 16, PM 13:40-15:00
Room K
Discontinuities

Chairs : J. Citerne, P. Kennis

Efficient Numerical Method for Microstrip Discontinuities Analysis

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The integral formulation combined with the method of moments, particularly the Galerkin's procedure, is a very powerful and flexible numerical tool for characterizing planar structures **[1-4]**. It is used in this work for the characterization and modeling of microwave planar transmission lines structures such as gap and right bend discontinuities. The algorithm we have developed determines the scattering parameters for these two structures through a selection of localized Roof-Top basis functions. The original work we have developed is mainly, the introduction of triangular sources which allow a better description of the problem within the base of Roof-Top trial functions in comparison to the impulse sources that have been widely used in the literature **[5]**. Then, eliminate the bouncing effect due to the abrupt change of the impulse source to obtain a faster convergence of the input impedance Z_{in} for different dimensions of the source.

It has been also necessary to introduce between the applied source and the considered structure a coupling two-port network to model the mismatch between the computed and the actual values of Z_{in} (Fig. 1). It is shown through an intensive study that the series impedance Z_s remains very small for a wide range of frequencies. Hence, only a shunt impedance Z_p and a transformer n can model accurately the impedance mismatch. A short-circuited microstrip line of known impedance has been used to validate the experimental data for Z_{in}.

The results we have obtained using the developed algorithm, compare well with those published by other authors **[2, 3]** for 80 basis functions and 10 000 modes. The magnitude of S_{11} for both structures are shown in Figures 2 and 3, and the convergence curve for Z_{in} as a function of the number of the triangular basis functions used is shown in Fig. 4. We should note that the use of a two dimensional FFT for our matrix system has greatly simplified the analysis and, consequently, a large computing time has been saved.

The presented approach has been successfully applied to many planar microwave structures including nonsymmetric ones. A further work is going on for other test functions to improve both the convergence and the accuracy of the proposed algorithm.

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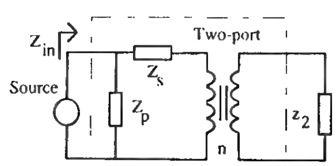

Fig. 1 : Equivalent circuit for the coupling two port network

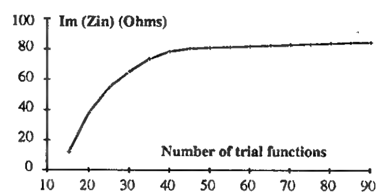

Fig. 4 : Convergence of Im(Z_{in}) versus the number of trial functions for a given number of TE and TM modes

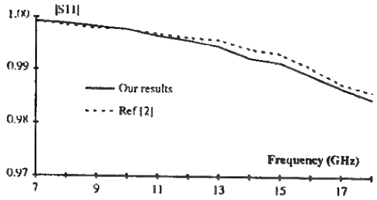

Fig. 2 : S_{11} parameter for a gap discontinuity a=c=6.35 mm ; h=0.635 mm ; w/h=1 ; g=0.381 mm

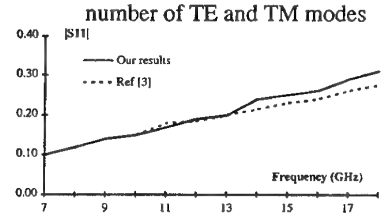

Fig. 3 : S_{11} parameter for a Right Bend discontinuity a=b=12.7 mm ; c=3.18 mm ; h=0.635 mm ; w/h=1

Efficient Analysis of Passive Microstrip Elements Using the Matrix Pencil Method

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An efficient approach for the full wave analysis of passive microstrip elements using the matrix pencil method [1] is proposed. This approach is based on the Mixed-Potential-Integral-Equation (MPIE) and on the Method of Moments (MoM) [2] applied in the spatial domain.

Spectral domain Green's functions for the vector and scalar potentials are first expressed in terms of the generalized Transverse Magnetic (TM) and Transverse Electric (TE) reflection coefficients [3]. These functions are approximated by a sum of complex exponentials using the matrix pencil method. Spatial domain Green's functions are then evaluated analytically using the Sommerfeld identity, thus the numerical integration of the inverse Hankel transforms of spectral domain Green's functions is avoided. This approach is very robust and can be applied to various microstrip structure configurations without previous adjustment of the approximation technique parameters.

The tangential electric field on the plane of the conductors is expressed in terms of the surface current density, expanded in a rooftop basis functions, and the closed spatial domain Green's functions for the vector and scalar potentials. The Galerkin-MoM matrix elements expressed by integrals are evaluated analytically after a Taylor series expansion of the integrands [4].

The spatial MoM method using the matrix pencil has been applied to a right angle band [5], and to a symmetric meander [6]. The scattering parameters are obtained using their formal definition in terms of normalized incident and reflected wave components of the current. The incident and reflected traveling waves of the dominant mode at the ports are evaluated using the Prony's method [7].

The results of the numerical simulations show that this approach is fast and efficient. The contribution of this work in using the matrix pencil method [1], is to give more robustness in obtaining closed-form spatial domain Green's functions.

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Full-Wave Analysis of Multimode Waveguide Discontinuities

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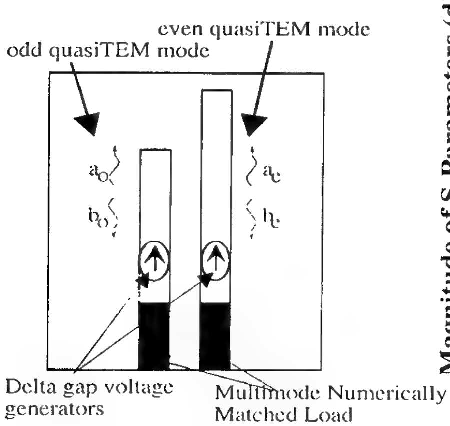
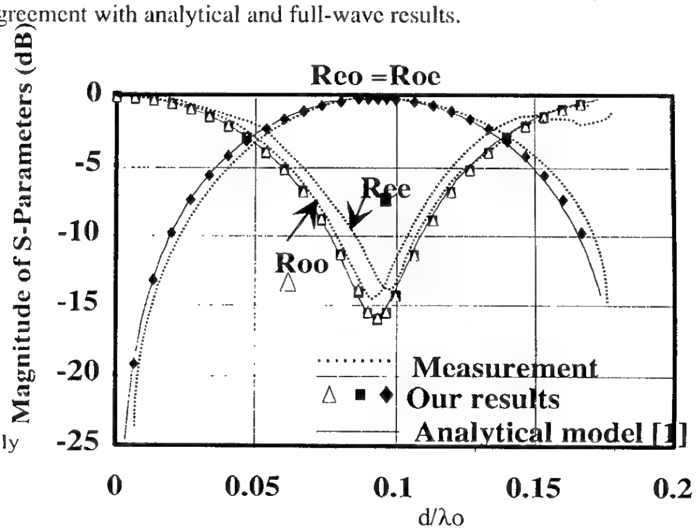
This communication presents a full-wave analysis of multimode waveguide discontinuities using a Spectral Domain Approach. Based on an Electric (or Magnetic) Field Integral Equation formulation, the electric (or magnetic) current distribution on the device is solved by the well known Galerkin's Moment Method. The generalized scattering parameters are numerically measured with the help of efficient Multimode Numerically Matched loads placed at each physical port of the discontinuities. Multimode Numerically Matched Loads are simulated by imposing the cancellation of the reflected waves on the terminating lines. With that in mind, the Matrix Pencil technique is used to decompose the currents along the lines into forward and backward travelling waves, yielding scattering parameters of device. The analysis of both microstrip coupled lines and coplanar lines asymmetric discontinuities is presented and successfully compared to experiments and available published results. As example, an asymmetric microstrip coupled line open-end is studied. In this case, mode conversion leads to a 2x2 scattering matrix between the modal amplitudes. For example, R_{oe} is the reflection coefficient of the odd quasi-TEM mode due to the incident even quasi-TEM mode of unit amplitude. The Multimode Numerically Matched Load is placed before the delta gap voltage generators in order to avoid reflection waves from the excitation mechanism. For the sake of comparison, an analytical model is also applied to analyze the mode conversion [1]. A multimode TRL calibration is also used to derive experimental multimode S parameters [2]. These measurements are in excellent agreement with analytical and full-wave results.





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Analysis of Discontinuities in a Rectangular Waveguide using Hybrid Numerical and Spectral Techniques

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The analysis of inductive obstacles and steps in rectangular waveguides has been a major field of research in recent years. This problem has already been solved using classical methods when the geometry of the obstacle is perfectly circular [1], or numerical methods are used to solve the problem otherwise [2]. In this paper a new, accurate and efficient hybrid technique [3], originally designed for solving scattering problems in open space, is now adapted in order to analyse the presence of discontinuities in rectangular waveguides.

The guided problem is solved in two steps. In a first step the metallic plates of the rectangular guide and the discontinuities are split into a number of individual scatterers. Each scatterer is then characterised individually using a numerical method (Method of Moments). This characterisation provides a scattering matrix for each object that relates the cylindrical spectrum of the incident wave to the spectrum of the scattered field by that scatterer. In a second step the mutual coupling between all scatterers is efficiently analysed iteratively, using analytical spectral techniques. As a result, the scattering problem is fully characterised and the response to any excitation can be immediately obtained. This method provides great accuracy as a numerical method is used for the characterisation of individual objects, but an analytical method is used for solving the coupling among scatterers.

This new iterative method allows the analysis of multiple obstacles of arbitrary shape in a rectangular waveguide, and the visualisation of the electromagnetic field in all points of the waveguide, as well as the retrieval of admittance or scattering parameters of the waveguide problem.

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Session F07
Thursday, July 16, PM 13:40-17:20
Room B/C
Conformal and Smart Skin Antennas

Organiser : A. Priou
Chairs : A. Priou, G. Washington

Electromagnetic Smart Structures

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One of the future applications of smart structures and materials for military aicraft of new generation could be the electromagnetic smart skin antennas integrated on the aircraft.Military aircrafts contain a proliferation of antennas to support advanced weapon system avionics.A tendency is to reduce the number of antennas sites on an aircraft to a minimum set of multifunction smart skin apertures that will provide equivalent or superior coverage and that will satisfy all the requirements of advanced weapon system avionics.Up to 50% of the air vehicle could be used for embeddement of antennas.Controlable and reconfigurable antennas or conformal antennas are needed for mission flexibility and for reducing component failure or battle dammages.Payoffs are mainly cost saving and weight saving per aircraft with additional properties such as improved low observable performances, supportability and drag reduction, etc...

After a brief examination of the elementary radiating element, the adaptive antenna and the antenna array, we are passing through the electronic scanning or sterring antenna array in order to approach the conformal antenna array.We present, after, the concept of electromagnetic smart skin antenna arrays that can be developped and integrated to future military or civilain aircrafts.A lot of examples will be given.We will adress the critical enabling technologies required to implement an electromagnetic smart antenna.We will show, also, the main advantages of such new technologies and concept for military aircraft of new generation (benefit and payoffs).

Smart Electromagnetic Structures : A New Paradigm for Microwave Technology

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The work in this study presents preliminary results on the modeling and development of Smart Electromagnetic Structures (SEMS). SEMS are electromagnetic structures that utilize mechanical and electrical principles to enhance electromagnetic performance. Three initial concepts are being developed. Modeling and control of active aperture antennas, Modeling and control of active spiral antennas, and Modeling and control of active microstrip patch antennas

Modeling and Control of Active Aperture Antennas

Recent studies have shown that reflector surface adaptation can achieve significant performance enhancement without the complexity and cost associated with phased array technology and. The work proposed in this study develops a class of antennas capable of variable directivity (beam steering) and power density (beam shaping). The actuation for these antennas is employed by attaching polyvinylidene fluoride (PVDF) film or PZT (Lead Zirconate Titanate) patches to a metalized mylar substrate. A voltage drop across these materials will cause the material to expand or contract. This movement causes a moment which causes a moment to be developed in the structure which causes the structure to change shape. Several studies of flexible structures with PVDF films and PZT patches have shown that cylindrical antennas can achieve significant deflections and thereby offer beneficial changes to radiation patterns emanating from aperture antennas. In this study, relatively large curved actuators are modeled and a deflection vs. force relationship is developed. This relationship is then employed in simulations where the far field radiation patterns of an aperture antenna are manipulated. Finally, the deflection versus voltage relationship is verified using experimental methods.

Modeling and Control of Active Spiral and Patch Antennas

Spiral patch antennas are inherently broadband in both directions. In many applications however, radiation is only needed in one direction. To eliminated radiation in the unwanted direction a ground plane is usually employed on that side of the antenna. This ground plane eliminates the problem associated with radiation in two directions, however in doing so it eliminates the broadband effectiveness of the antenna. Basic calculations show that once the ground plane has been added, the wavelength (lambda) of the resonant frequency is restricted to lambda=4*d where d is the distance between the ground plane and the spiral antenna. If one could develop a mechanism to vary the distance between the patch and the ground plane without greatly effecting the radiation pattern, then lambda can be varied and the antenna can selectively "tune" itself to a particular frequency. One solution to this problem is a mechanically active spiral patch antenna. In order to tune a broad range of frequencies, distances between the ground plane and the patch of up to 1 cm were needed. The design featured a unique combination of one static platform and one dynamic one. Since a high bandwidth, low stroke, and low power actuation system was needed the dynamic platform is actuated by piezoelectric RAINBOW (Reduced And INternally Biased Oxide Wafers) stack actuators. RAINBOW's are a type of piezoceramic actuator that is capable of relatively large deflections when compared to conventional PZT stacks. Various control techniques to include positive position feedback and lag control have been employed to counteract the effects of hysteresis and creep on the actuator. Since the use of metal components can degrade antenna performance, emphasis was placed on synergy in the design process.

A similar methodology can be extended to rectangular microstrip patch antennas. The microstrip patch antenna is an ideal candidate when low profile, light weight, and small size is needed. They are rugged and can be manufactured easily using well known photo-etch techniques that are standard with modern electrical and microwave integrated circuits. A major weakness of the microstrip antenna is its narrow impedance bandwidth which typically ranges up to a few percent depending on the substrate dielectric constant, the dielectric thickness, and the geometry of the patch. Frequency agility and bandwidth enhancement has been the subject of many studies to include the following. Embedding control elements in the patch, Proximity coupling techniques, impedance matching techniques, and the addition of a parasitic patch (The parasite patch is identical to the parent patch except it does not have a ground plane. In this study a mechanically active microstrip patch antenna is developed. The antenna consist of a microstrip patch antenna and a parasite that is mechanically actuated to vary its distance. The parasite is housed in a novel configuration that is actuated by RAINBOW stack actuators.

A third project uses the ferroelectric properties of Barium Strontium Titanate BaSTO to change the dielectric constant of the substrate between the two patches. The net effect is the same as varying the distance between the patch and the parasite.

On Layer and between the Layers Connections for Smart Skin Applications

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The new technologies make it possible to obtain extremely thin and flexible phased array antennas, even shape adjusted to the mechanical supporting structure underneath. This emerging, new kind of phased array antennas is called smart skin antennas.

A phased array antenna consists of the radiating aperture, the feed network and the signal control devices. The modern semiconductor technology allows for a high degree of integration in the feed network and signal control circuitry. The size of the radiating aperture, however is not affected by the technological progress since the spacing and the grid of the antenna are determined mainly by the radiation pattern and the frequency. There is no fundamental difference in the basic building blocks between the traditional phased array and smart skin antenna. However, the way in which the smart skin antenna is assembled is entirely different.

There are two main solutions to organise a smart skin phased array:

- "tile" architecture, Fig. 1
- "brick" architecture, Fig. 2

The paper presents some results on new technologies for planar connections using anisotropic and isotropic conductive adhesives as well as new types of vertical connections between the antenna layers.

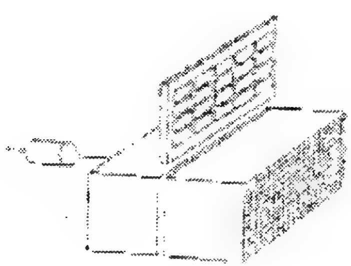

Fig. 1. "Tile" architecture for a phased array antenna.

Fig. 2. "Brick" architecture for aphased array antenna.

A 64 Element Broad Band Volumetric Array Antenna

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In a volumetric array antenna the radiating elements are positioned at random locations within a three dimensional volume - typically a sphere. Volume arrays have potential advantages over planar or conformal arrays in terms of increased scan coverage, efficiency and sidelobe performance. In addition, the random element arrangement produces a non-periodic structure which can be adapted to provide a low RCS.

The paper will present experimental results obtained from a 64 element volumetric array designed for broad band operation. The experimental volumetric array consists of 64 elements arranged in spherical volume of radius 200mm. Each element is a 7 segment log periodic dipole array designed to provide wide band operation over the range 6GHz to 16GHz. The current array is configured to provide optimum scan performance in the H-plane as, in this orientation, the coaxial feeds are orthogonal to the radiated E-field.

At present the volumetric array has no beam forming network and so the array scan performance can not be measured directly. Therefore, the main beam scan characteristics were synthesised from the measured embedded element patterns. This approach allows accurate predictions of the array performance that include the effects of inter-element coupling. Main beam patterns were synthesised at H-plane scan angles within the range $\pm 85^\circ$ at frequencies of 8GHz, 10GHz, and 12ghz.

The results show that the main beam of the array can be scanned over an angular range of $\pm 90^\circ$. The beamwidth of the scanned main beam does not degrade with scan angle, but remains constant over the entire scan range. A peak sidelobe level of around -10dB is observed at each frequency and scan angle. The average sidelobe levels of the scanned beam patterns are also relatively independent of frequency and scan angle, and correspond well with the theoretical value of -18dB

The optimum performance of the array is governed by the element characteristics, and occurs at the mid-band frequency of 10GHz. At this frequency the gain of the main beam varies by less than 3dB over the full scan range.

Numerical and Experimental Tools for Conformal Array Performance Investigation

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Current conformal antenna array R&D at FGAN-FHP is in an early research state, which concentrates on the development of numerical and experimental tools to study the physical and functional performance of conformal arrays. The contribution will give an overview on our work with respect to :

Generic Array Modelling

Several model approaches /1/ with increasing complexity are considered. A scalar model takes into account coupling and diffraction in a simple way. A polarimetric extension of the scalar model is investigated without coupling. Finally a polarimetric model taking into account generic coupling and diffraction is developed. By means of these models generically critical physical effects and their influence on beamforming can be studied at least qualitatively.

Beamforming Algorithms

Using the polarimetric array model some basic properties of pattern synthesis for 2- and 3-dimensional conformal array structures can be studied /1/. Beamforming is illustrated for small and large field of view array geometries. Frequency dependence of pattern synthesis for conformal arrays can be addressed.

Radiating Surface

Several conformal experimental test arrays are being realised using a partial antenna CAD /2/. This consists in CAD of single polarimetric patch antennas of different design for different bandwidths using complex design software. Electromagnetic array performance of these elements is obtained by measurement.

Functional Demonstration System

An experimental multichannel system /2/ is being realised in order to measure and demonstrate electromagnetic and system performance of conformal test arrays. Many electromagnetic near and far field array parameters can be obtained from multichannel antenna measurements. Beamforming algorithms can be incorporated in order to investigate their performance with respect to test arrays. Pattern synthesis for test arrays with small and large field of view can be demonstrated experimentally.

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Pattern Synthesis for Large Conformal Array Analysis, Using Two-Port Elements for Polarimetric Correction

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Pattern synthesis for conformal arrays may be based on an electromagnetic equivalence principle. It states, that different radiating antennas are equivalent, if they produce in a given region of space the same field distribution.

Taking a planar array as reference antenna, the weights of a conformal array can be computed using the least mean square principle [1] by searching for the minimum euclidian distance between the co- crosspolar electric field components of the planar array and the corresponding electrical field distributions produced by the conformal array. This results in a system of linear equations (Normal Equations), which can be solved for the element weights. This process will be called diagram-inversion, but other numerical methods may be applied as well.

Numerical simulations of large conformal arrays consisting of several hundred elements, positioned on various single and double curved array apertures, will show the large potential of such arrays, especially considering a very large field of view.

On the other hand these conformal arrays require the use of two port array elements. As an example it will be shown, that a linearly polarized co-polar pattern requires the excitation of both of the polarimetric orthogonal ports of the conformal array elements - sometimes in a major part of the array aperture. This will be illustrated by presenting amplitude- and phase- taper of conformal apertures, related to calculated weighting coefficients of the conformal array under consideration.

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Analysis of Conformal Microstrip Lines and Antennas Using the Nonorthogonal FDTD Method

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The Finite-Difference Time-Domain (FDTD) technique has been proved to be an effective and convenient tool for the time domain analysis of various electromagnetic problems. Its main advantage is the possibility of broadband analysis. Nevertheless, one of the most significant drawbacks to the classical FDTD formulation is the requirement that the mesh be orthogonal in nature. This is a highly restrictive characteristic because many pratical geometries contain oblique angles as well as curved boundaries. A common approach to analyzing objects with arbitrary geometries with the Yee [1] algorithm is to use staircasing to model the curved surfaces. However, this procedure introduces errors due to the inaccurate modeling of the geometry. Another solution which enables to avoid this approximation is the extension of the standard Cartesian FDTD method to a nonorthogonal mesh [2]. Although it results in a more complex formulation, this extension appears as a very versatile and powerful tool. As it uses general curvilinear coordinates, it is not restricted to any particular geometries and will be particularly suitable to study conformal printed structures.

This paper presents the analysis of cylindrical striplines and cylindrical microstrip lines using the FDTD in curvilinear coordinates. Numerical results for the characteristic impedance and the propagation constant are in good agreement with the published results [3]. Some comparisons with our measured datas are also provided.

The method is currenty applied to microstrip antennas conformed on a cylindrical body. The obtained results are compared with our measurements.

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Improved Asymptotic Solutions for the Calculation of the Mutual Coupling between the Elements of a Conformed Array of Patch Antennas

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The coupling between the elements of a conformed array of patch antennas on a convex surface is investigated by asymptotic high frequency techniques.

In a first step, expressions for the components of the dyadic Green's functions for z- and ϕ- directed point sources of electric currents in the presence of a layered cylindrically obstacle are developed as spectral integrals over longitudinal and azymuthal wave numbers [1] [2].

In a second step, the spectral integrals are evaluated asymptotically for field points located on the surface of the outermost layer.

Different asymptotic expansions have been established whether the field point is located outside or inside the paraxial region. Outside this region, where $k_1a >> 1$, a being the radius of the surface of the coated cylinder, zero and first order terms with respect to the parameter $m = (k_1a)^{1/3}$ have been derived. These terms which describe the effect of torsion of the geodesics followed by the creeping rays emanating from the source tend to infinity in the paraxial region. A different expansion, valid inside the paraxial region is obtained by expanding the solution in a Taylor series with respect to k_1a and keeping a few terms. This expansion blows up when k_1a takes on large values. However, when a renormalization procedure is applied, it has a common domain of validity with the outer expansion and can easily be matched with it.

The validity of the dyadic Green's function is checked by comparizon of the results obtained by exact numerical calculation of the spectral integrals.

An heuristic extension of the formulas to a coated 3D surface defined locally by its principal radii of curvature is also presented and compared with the solution given in [3].

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Microstrip Patch Antenna on Conical Structures

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Thanks to their small size and low weight, microstrip patch antennas are easily conformed to their mounting surfaces. It is for that very reason that conformal microstrip patch antenna arrays are used in many applications for aircraft mobiles and satellite communications. However, most of studies on this subject have especially analysed rectengular patches mounted on cylindrical surfeces to producc omnidirectional patterns in the circumferential plane of cylinder. This paper presents a parametric study of microstrip patch antenna on conical surfaces 'Fig. 1)fed in an original way (Fig. 2). In all the study, the radiating element is considered to be small compared to the curvature radius of the mounting body. Conformal arrays are studied by a theoretical analysis taking into account both the positions and the orientations of patches on the surfaces, and their excitations conditions in amplitudes and phases. The far field radiated by one element is first calculated using analytical functions. The total field is then obtained by a coherent summation of the elementary contributions of each patch in the array made up of one or several ring sub-arrays of different radii. Anew method to feed conformal microstrip arrays is used and the measurements are compared to the results obtained by a classical probe feed solution. This technique uses a bent CPWthin substrate (height = 0.125 mm). The patch is electromagnetically coupled to the field propagating in the CPW transmission line through a slot at the end of the coplanar line. Tha apertur allows to insert the slot ended CPW in the antenna ground plane and then to ensure electrical continuity. The results are described and discussed.

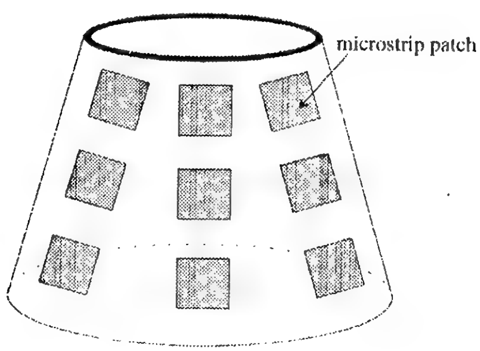

Fig 1.: Multi ring conical array

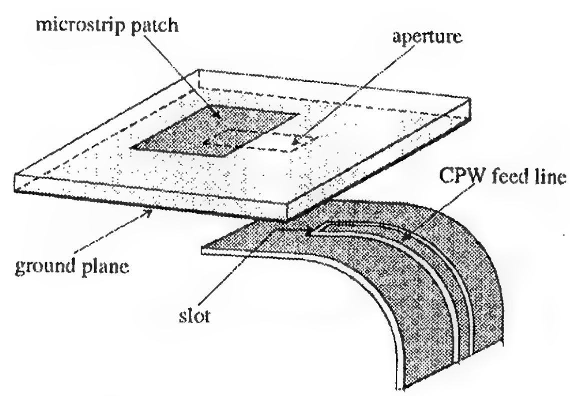

Fig 2.: Microstrip patch fed by bent CPW

Conformal Array Antenna for Aircraft Application

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In this paper, THOMSON-CSF presents a low cost conformal antenna concept. This antenna, basically an active reflector array, is composed of a Microwave Printed Circuit Board [PCB], on which 2 - 3 - 4 bits planar phase shifters are etched, and of a Digital multilayer PCB which made the interconnection between the PIN diodes controlling the phase shifters and their silicon driving circuits, highly integrated and provided on the civilian market. Because no microwave connection is necessary, and because the digital components used in this antenna are issued from mass production, this antenna is expected to be very low cost. On the other hand, the thickness of the antenna is reduced ($\lambda/10$), so it is possible to made it conformal to the outer skin of an aircraft, and then to integrate it in a very reduced place.

From the technological point of view, the manufacturing of this conformal array antenna involves a great deal of new technologies :

- Realisation of multilayer Printed Circuit Boards with a curvature, in order to fit to the radome external shape : *conformal PCBs*. These PCBs will support the radiating elements and the distribution circuits (microwave and digital). It could be one substrate or two separate ones.
- Design of integrated power supplies and use of an efficient cooling technique : integrated power supplies mean high density combined with an efficiency greater than 0.9 and with a limited thickness (5 to 10 mm). The cooling technique should take into account the necessary flat temperature distribution over the antenna (for RF performances).
- And, of course, a simple and reworkable technology for assembling all those bricks.

Thomson-CSF has already technological programmes which aim to solve these problems :

- The BRITE-EURAM TRILAP programme (managed by Thomson-CSF, with BAe, Exitech, Olivetti, amongst others) deals with a manufacturing process for *conformal PCBs* mixing microwave and digital layers. This 3-years project (1997-2000) supports also the development of the 3D routing CAD tools and of a 3D patterning process using a laser (excimer, CO2 or YAG) for the imaging of conductors and vias in 3D.
- New generations of cooling systems are under development in the european EUCLID CEPA 4 and ASAAC programmes. Two main options are investigated : flat heat pipe cooling and liquid-flow-through cooling. For the first one, the basic technique is phase change of a liquid : its main interest is a flat temperature distribution over the heat pipe which thickness is less than 3mm. The second one is based on the use of compact heat exchanger, which thickness is also less than 3mm : a liquid is used (instead of air), up to very high power dissipation.

This paper concludes on the possibility to manufacture active conformal arrays, or more precisely conformal antenna including microwave power generation (HPA MMICs) distributed into T/R modules. Ultra thin T/R modules could be mounted parallely to the radiating panel instead of perpendicular (*Tile* Modules instead of *Brick* Modules in the American terminology). The obtention of such modules is already necessary for reaching the objective of low cost active flat antennas, because they are particularly well suited to a collective manufacturing process. Today, the *Tile* T/R Modules technology is supported by the french MOD in a large programme of development of low cost T/R modules. The basic technologies are 3D interconnections and packaging, collective interconnections between MMICs using a polymer film, hybridisation of MMICs on an active silicon substrate, and HBT technology for realising the power amplifiers with an expected 60% Power Added Efficiency (PAE) in X-band (10W).

Session G11
Thursday, July 16, PM 13:40-16:00
Room M
Photonic Crystals : from Microwave to Optics

Organiser : J-M. Lourtioz

Second part :

Chairs : J-M. Lourtioz, E. Yablonovitch

Microwave Antennas on Photonic-Crystal Substrates

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Microwave integrated circuits (MICs), particularly monolithic ones on GaAs or Si, have long been challenged by the fabrication of efficient planar transmit and receive antennas at the dielectric-air interface. The problem stems from the fundamental division of radiated power between the dielectric (permittivity, ε) and air, which for an infinitesimal antenna goes as $\varepsilon^{3/2}$. Once radiated into the substrate, the power is trapped there by total internal reflection or is attenuated by dielectric or metallic absorption mechanisms. Five years ago the author announced a promising approach to this problem through transforming the substrate into a three-dimensional photonic crystal. By choosing the photonic crystal to have a strong photonic stop band along the direction perpendicular to the substrate and by choosing the driving frequency of the antenna to lie in this band, it was shown that the majority of the radiation from the antenna went into the air, not the substrate. And because the photonic crystal is a distributed reflector, this process could occur without shorting out the driving gap of the antenna. Hence, the antenna gain, and the associated antenna efficiency, could be very high along desirable directions into free space.

This talk will address progress that has occurred in the past few years, starting with work on conventional (all-dielectric) photonic crystals. It has been shown that the orientation of an elemental antenna relative to the unit cell and the crystal axes strongly affect the radiation pattern. For example, in certain orientations the zenithal gain of a half-wave resonant dipole is over 10 dB, exceeding the gain of the same antenna supported in free space one-fourth wavelength above a metallic ground plane. This leads to the notion of "substrate focusing", similar to what occurs for an antenna feeding a reflecting dish. Additional progress has been made in the form of the photonic crystal. Three years ago, we developed the metallodielectric photonic crystal (MDPC) to reduce the thickness of the substrate required to make an efficient antenna, and to improve the design latitude by lifting the requirement on high-permittivity materials. More recently, dipole antennas have been measured on MDPC substrates with even higher broad-side gain, cleaner radiation patterns (i.e., less scalloping), and less sensitivity to antenna orientation than occurs on conventional photonic crystals.

+This work was sponsored by the U.S. Army Research Office.

Arrays Grating Lobes Reduction Using Metallic Photonic Band-Gap Materials (MPBG)

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In the last few years, people renewed their interest on periodic metallic wire structures which can also be called metallic photonic band-gap materials (MPBG). A lot of theoretical and experimental studies have been published showing the potential applications of PBG as antenna reflector [1]. The interactions between antennas and MPBG, when they are very near, have been pointed out at frequencies within a band-gap [2]. Here, we study the possible array grating lobes (GL) reduction using MPBG. Some similar works have been done by R.J. Mailloux [3]. But in our case, the antenna and the MPBG material are very near and so the coupling between the two elements is strong.

The GL reduction can be obtained by different means. Previous studies of MPBG [2] showed that the reflection coefficient phase depends on the plane wave incident angle. The first mean could be obtaining a destructive interference between the direct emission and the reflected wave, in the GL directions, whereas the interference is still constructive on the main axis. An other possibility is to find a structure with a band-gap for normal incidence whereas it is a propagation band for GL directions of emission. Then, the last possibility, is to find a structure which has good propagation characteristics for normal incidence whereas it reflects GL.

Different structures (2 or 3 dimensional), period, wire diameter have been analyzed with an array composed by 3 half-wavelength dipoles. The greatest GL reduction have been obtained in the case of propagation of the main lobe inside the MPBG. The influence of the dipoles position regarded to the MPBG have been analyzed to obtain the greatest radiated power and the best coupling between modes outside the MPBG (array near field) and inside (inner modes).

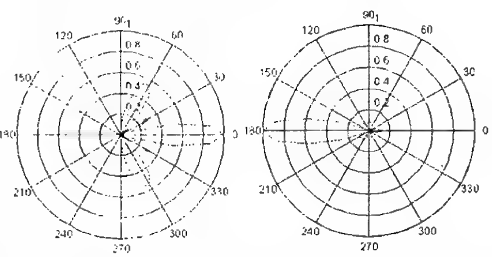

fig. 1 - Array antenna above metallic reflector and between 2 MPBG materials (a reflector and an angular filter), at 2.5GHz

This GL reduction can be used only in limited scan applications. But this limit clearly depends on the way GL are reduced. Simulations have been performed with NEC (numerical electromagnetic computation). Experimental results will be shown during the conference.

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Photonic Band Gap Materials for Microstrip Patch Antennas

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During this last decade, a new kind of materials has been the subject of growing investigations : the Photonic Band Gap structures (P.B.G.) [1,2]. Such materials have the particular property of diffracting electromagnetic waves whatever the direction they come from. Moreover, this phenomenon can be observed on a large bandwidth. Such a material was born from an idea of Yablonovitch [3,4] who thought that if semiconductors were able to diffract X ray, it was possible to imitate the atom arrangment at a greater scale in order to have the same properties for millimeter or optical waves.

For the theoretical part of our study, we have extented the F.D.T.D. approach to deal with periodical structures such as P.B.G. ones [5]. This method will be applied in the antenna domain in the millimeter frequency range.

In order to validate our code, a two dimensionnal P.B.G. structure constituted by rows of rods arrangment has been studied and we have realized an experimentation to measure its transmission coefficient. A comparison between theoretical and experimental results, for different kinds of structures (with or without defaults, square or triangular lattices...) has shown a very good agreement.

Such materials can have interesting applications in the microstrip antennas domain.They can be used as a substrate or a superstrate. A typical property of P.B.G. structures for such applications is to reduce the coupling between two radiating elements in an array as it will be shown. We have also studied the effects of using a P.B.G. material on the radiation pattern.

Conclusion

The knowledge of P.B.G. materials behaviour allows us to find different applications. The use of such materials in microstrip patch antennas domain has led to improvements of their characteristics.

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Band Gap Engineering in Micro-Wave PBG Material

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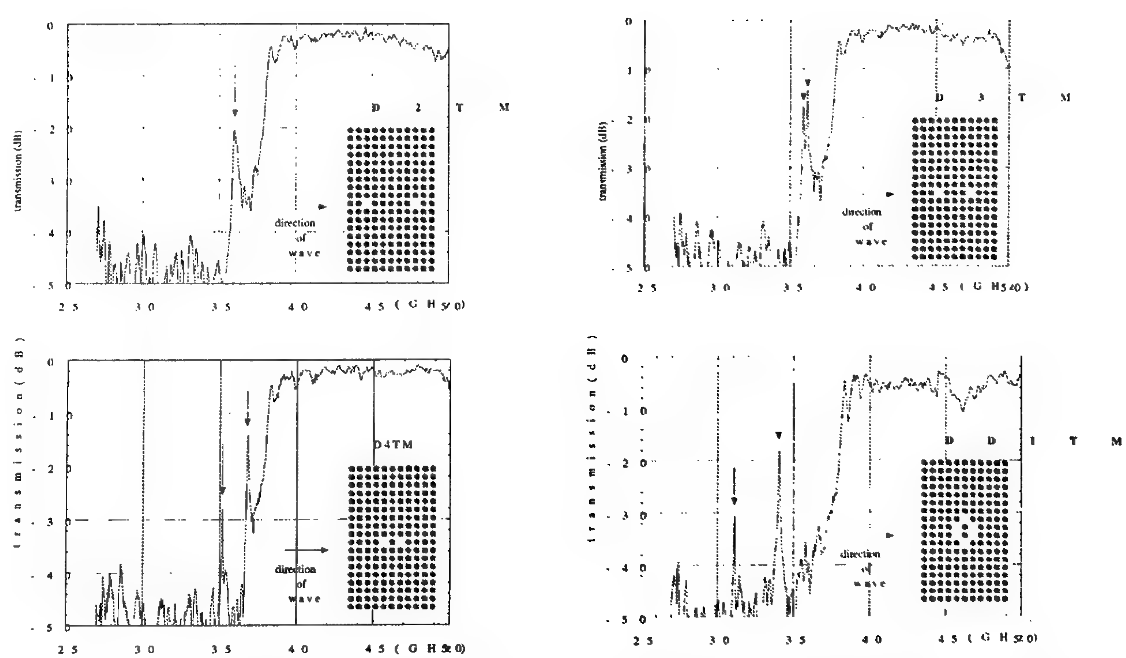
Materials with a periodically structured dielectric constant may exhibit forbidden photonic band gaps (PBG), that is, frequency domains where electromagnetic fields cannot propagate. The position and width of these forbidden gaps can be controlled via the geometrical parameters of the structures and the contrast between the different permittivities. PBG materials have potential applications to a variety of devices in the microwave domain such as waveguides, couplers, reflectors and antenna substrates. This work reports on first systematic experimental study of microwave defect in a dielectric and metallic square lattice PBG material. The goal of this work is the ability to modify on demand the band diagram of the material including several defects. Experiments are performed in the 27-75GHz frequency range. Different defect geometries are given in illustration. We have characterized dielectric and metallic square lattice of rods with several types of defects. The radius and spacing of the cylinders are respectively 1.5mm and 3mm. In dielectric lattice alumina rods are used with a permittivity of 9 and copper cylinders in metallic structure. Each type of defect has one or several resonance modes, depending of the distance and the coupling between them. If two modes are coupled, the spacing between the two corresponding peaks is function of the strength of the mode coupling. If several modes are present as for a waveguide in a PBG material, a broadening of the peaks may cause the appearance of an allowed transmission band in the gap. In metallic lattice we observe the same phenomenon with the difficulty of the impedance mismatch between the source and the crystal.



Comparison between four defect geometries and the corresponding resonance peaks in a dielectric square lattice of alumina cylinders with a radius of 1.5mm and a spacing of 3mm and a dielectric permittivity of 9. The incident wave is TM polarized. The arrows indicate the resonance peaks associated with defect. We may observe the split in two peaks and the increase of their spacing as the defects come nearer.

Theoretical and Experimental Study of Defect Mode in Graphite PBG Material

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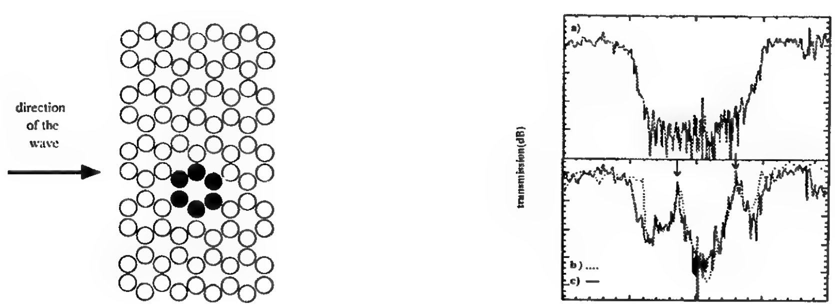
Photonic crystals have received a growing interest in the recent years since the first demonstration of a complete photonic bandgap (PBG) in a diamond-like structure at microwave frequencies. Indeed, the development of photonic crystals appears to be as a promising way to control spontaneous emission from optical sources. Besides, technological difficulties arising from the fabrication of three-dimensional periodic structures at optical wavelengths can be circumvented with the use of two-dimension PBGs in planar waveguide configurations. Theoretical studies of two-dimensional periodic lattices of dielectric cylinders have shown that essentially two types of structures can exhibit a complete photonic bandgap for electromagnetic waves propagating perpendicularly to the cylinders [1]. The first one is the triangular structure of cylindric holes in a material of high dielectric permittivity. The second structure is the hexagonal lattice of cylinders of high dielectric permittivity in air. Recent calculations have shown that a complete photonic bandgap can be obtained over a large range of filling factors from Å10% to 60%. Such a flexibility represents a real opportunity in terms of fabrication process. In a preceding paper [1] we have confirmed the theoretical predictions. The present work is then believed to be the first experimental and theoretical systematic study of defect mode in hexagonal lattices of identical dielectric cylinders (graphite structure). Experiments are performed at microwave frequencies between 27 and 75GHz. Transmission spectra for a TM polarized wave measured for crystals with different defect geometries are compared in detail with numerical calculations. Below the figure compares the numerical (b) and measured curve for the material with (c) and without defect (a). The measured transmission for this defect is quite equal to the transmission for the allowed band. In preceding work on defect in PBG material, the transmission rate was always 10dB lower. This result confirms the interest of the hexagonal bidimensional lattice.



Transmission rate in an hexagonal lattice (white dots) with an hexagonal defect (black dots) : (a) measured curve for the material without defect, (b) theoretical curve,(c) measured curve with defect.
The arrows indicate the peaks corresponding to the defect mode. The radius of the cylinders is 1.5mm, the distance between two rows is 2.89mm. Alumina rods are used with a permittivity of 9.

Reference

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Session G12
Thursday, July 16, PM 16:00-18:40
Room L
Superconducting Devices : Modeling and Desing

Organisers : I. Vendik, P. Guillon

Chairs : I. Vendik, P. Guillon

Modeling of pass-band HTS microstrip filters based on a parallel-array of half-wavelength resonators

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An increasing of the efficiency and quality of wireless communications requires to use high-quality devices and system components. The requirements to pass-band filters for the cellular communication systems are sufficiently strong. The filters should be compact and lightweight, they should provide a low insertion loss in a pass-band, sharp skirts of the characteristic and high power handling capability. The use of high temperature superconducting (HTS) thin films in microwave integrated circuits makes possible to realize pass-band filters with a low insertion loss and sharp skirts. Pseudo-interdigital filters [1] are most compact and useful for wireless communications in the frequency range 1-2 Ghz.

The design of pass-band filters with central frequency 1.75 GHz and pass-band about 4% was carried out. The HTS filters on isotropic and anisotropic (sapphire) substrate were developed as a parallel-array of half-wavelength microstrip resonators, fabricated, and measured. The modeling of these structures can be done using different ways. Note, that no one commercial software including full-wave analysis programs could provide the simulation results which are fully adequate to the measured ones due to lack of appropriate models accounting for HTS properties at microwaves. In order to simulate the filters characteristics we use some empirical methods modified to the HTS case. The closed-form models of HTS film surface resistance [2] and HTS planar transmission lines on sapphire substrate [3] are used. We investigated an influence of factors of different nature to the filter characteristics.

In order to increase the power-handling capability of the filters it is necessary (I) to increase the strip width so that there is more conductor available for carrying current; (II) to increase the line characteristic impedance by using a thicker dielectric or the lower effective dielectric constant; (III) to increase the film thickness. A possible appearance of nonlinear phenomena under high-power level should be taken into account at the filter design. The nonlinear model of microstrip resonator [4] was applied to analyze the nonlinear effects in the HTS filter.

The high-order HTS microstrip filters have been designed, modeled, and measured. The measurement results exhibit a high performance of the filters. A good accuracy of the simulation procedure based on closed-form models is observed as compared with the experimental data.

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Miniature Microwave Filters for HTS Applications

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***ALCATEL ESPACE - 16 Av. J.F. Champollion - 31037 TOULOUSE Cédex - FRANCE**

The expansion of HTS thin films through the various publications shows the great interest of microwave components manufacturers on the superconducting technology, especially for base station and satellite communication systems. We are interested in the bandpass filters because they are key components for these applications. When using superconducting devices, the absolute necessity to have a cryocooler to keep the circuit in working order implies that these ones must have the smallest dimensions as possible.

That's why we propose to use planar filters which can take a great advantage of HTS thin films : besides the size reduction and the possibility to combine active and passive functions, the superconducting films allow to practically eliminate losses due to conductors, which is especially significant when very narrow-band filters are required [1].

A four-pole elliptic function response bandpass filter was designed using an original single-mode cross open-loop planar resonator. The employed topology for the filter, presented on figure 1, is developed in [2]. The filter synthesis is done by fullwave electromagnetic simulators. Each coupling coefficient is determined separately to the others from simple structures. The complete circuit is finally simulated with dimensions obtained from all independant coupling rates. This 4-pole filter was fabricated on an aluminate substrate with gold metallization and measured at room temperature in a first time to validate theoretical results and to demonstrate its feasibility with superconducting materials. Simulated and experimental performances at 4 GHz are shown on figure 2. Good agreements are reported. The conception of this filter with an YBaCuO thin film on lanthanum aluminate substrate is now in progress.

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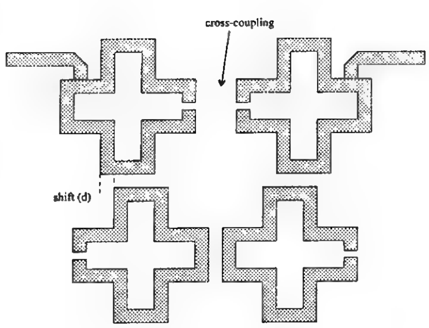

Figure 1 :
Layout of a four-pole elliptic function planar filter using single-mode cross open-loop resonators

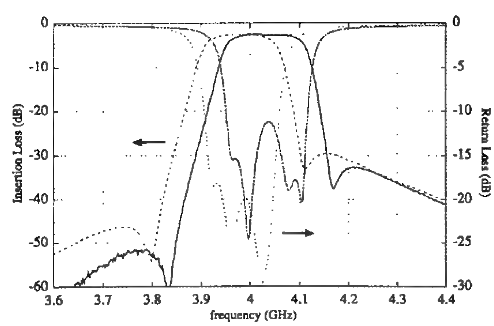

Figure 2 :
Simulated and measured performances of the 4-pole 4% bandwidth filter at 4 GHz on an aluminate substrate (e_r=9.8, h=0.635 mm) with gold metallization

HTS Filters for Satellite Output Multiplexers

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Introduction - The advance in the production of high temperature superconducting thin films has had an important impact on RF devices. Taking advantage of the low surface resistance R_s of these materials, extremely low loss and small size passive microwave components can be fabricated. In the field of high power satellite applications the improved RF performance of these devices can be utilized to compensate the additional cooling power, whereas the reduced size and weight directly pays off due to the high launch costs of about $70.000 per kg of mass.

Specifications - This paper reports on advances in the development of high temperature superconducting bandpass filters for 3.4 - 4.2 GHz (extended C-band) output multiplexers of communication satellites. The filter response is specified to be 40 MHz bandwidth four-pole with quasi-elliptic frequency response and power handling capability of 60 W transmitted power. The unloaded Q-factor of the filter resonators is required to be higher than $1.5{\cdot}10^5$ in order to keep the dissipated power per resonator below 100 mW when the transmitted power per channel exceeds 60 W. For this power level the individual resonator has to handle an oscillating power of 15 kW without considerable degradation of the unloaded Q-factor and with sufficiently low intermodulation.

Approach - A concept of "edge-current-free" disk and ring resonators operating at TM_{010}-mode has been proposed [1], [2], which is suitable to handle the extremely high oscillating powers. With these resonators on 1 mm thick $LaAlO_3$ and sapphire substrates the required value of the unloaded Q-factor can be obtained at temperatures of 50 K and 70 K respectively. The Q-factor of the resonators on $LaAlO_3$ was degraded by about 10% relative to the low-field value at an oscillating power level of about 35 kW which is at least two times more than required value.

Results - As a first step to the required filter configuration a two-pole Chebyshev filter based on this concept was designed, fabricated and characterized [3]. The insertion loss of the filter was measured to be unchanged up to the transmitted power of 100 W.
Based on the two pole filter concept this paper presents a quasi-elliptic four pole filter which meets the above mentioned requirements for the C-band satellite output multiplexer. This filter has beed designed utilizing two two-pole structures and introducing two additional coupling elements. The filter has been fabricated and tested and can handle the specified transmitted power of 60 W without noticeable degradation of the resonators unloaded quality factor.

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Modeling of coupled HTS coplanar waveguides.

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The uniplanar high-T_C superconducting (HTS) lines as the coplanar waveguides look very attractive for applications in narrow-band filters due to their very low insertion loss. The simple model of the coupled coplanar lines (Fig. 1) was developed using the conformal mapping technique to find the propagation characteristics for the even and odd modes, and the coupling capacitance as well. The model presented has no limitations on the geometric parameters in contrary to [1]. The simulation results are presented in Fig. 2. The finite substrate thickness is taking into account by the partial capacitance method. The attenuation coefficient is calculated accounting for the microwave surface impedance of the HTS thin film and non-homogeneous current distribution. The results simulated using this model are compared with the data from [1], and the results of full-wave analysis and measurements.

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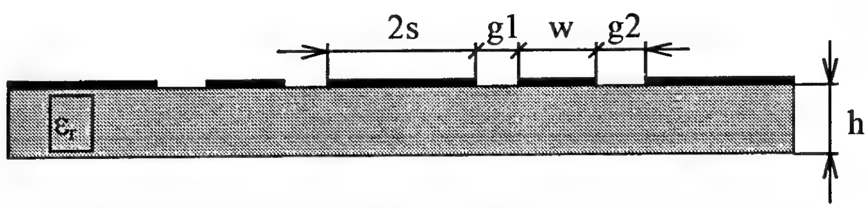

Fig. 1. Cross-section of coupled coplanar waveguides.

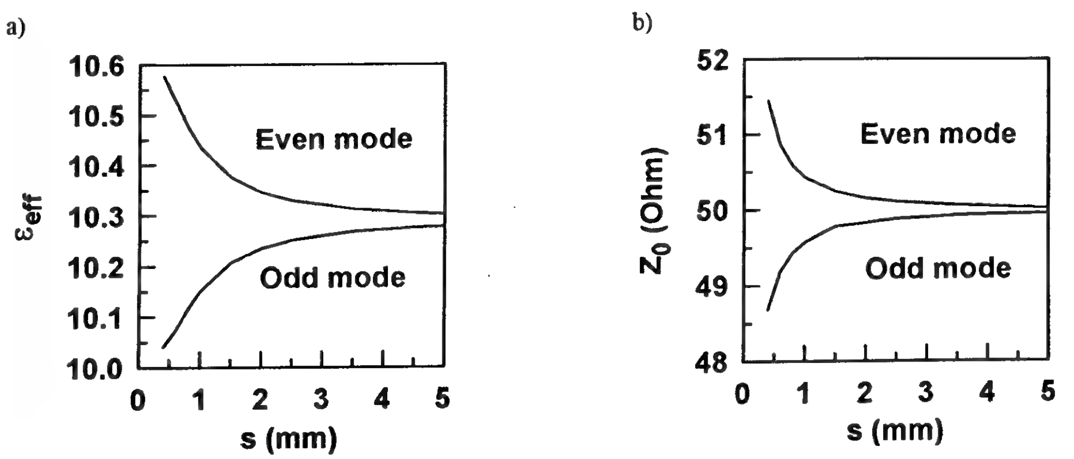

Fig. 2. Effective dielectric constant (a) and wave impedance (b) of the coupled coplanar waveguides : w=0.37 mm, g1=g2=0.5 mm, h=0.5 mm, e_r=24.

Quasi-optical Phonon Cooled NbN Hot Electron Bolometric Mixers for Terahertz Frequencies

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In recent years, significant advances have been made in the development of heterodyne receivers of a submillimeter wave range with a noise temperature approaching the quantum limit [1]. these receivers utilize Nb superconductor-insulator- superconductor (SIS) tunnel junction mixers. However, at frequencies higher than the energy gap for Nb (700 GHz) and especially higher than 1 THz the noise temperature grows drastically. Only Shottky diode mixers can be used here, they are much noisier and require a high local oscillator (LO) power.

Recently, superconducting hot electron bolometric (HEB) mixers, i.e. planar superconducting film mixers utilizing hot electron phenomenon, have been demonstrated to show low noise at frequencies from the millimeter wave range up to several THz. It is expected that the use of such detectors in terahertz heterodyne spectometers will allow to achieve a performance much better than presently available for applications in airborne and spaceborne astronomy and atmospheric physics.

Two possible realizations of a superconducting HEB differ according to the type of electron cooling mechanism used either heat transfer to phonons via electron-phonon interaction [2] or out-diffusion of hot electrons from the HEB [3]. A breakthrough has been observed in the last year for both of them as far as the achievement of low noise temperature and large IF bandwidth is concerned.

In this paper we present recent results for spiral antenna NbN phonon cooled mixer in the frequency range 500-1100 GHz. Ultra-thin NbN films (3-3.5 nm thick) have been deposited on high resistive silicon substrates by reactive dc magnetron sputtering. Electron-beam lithography process was used to form 0.2 µm long and 0.2 µm wide bolometer strip across the center gap of Ti-Au spiral antenna. The substrate on which the device and antenna are integrated, was glued to an extended hyper hemispherical silicons lens. The mixer was mounted in a LHe cooled cryostat equipped with a Teflon window.

The double sideband (DSB) receiver noise temperature T_r was determined from the y-factor with a hot/cold load (300/77 K) in a signal frequency range of 500-1100 GHz and at intermediate frequency 1.5 GHz. The best DSB T_r value is less than 1000 K and the absorbed optimal local oscillator power is about 100 nW. these results are very promising for terahertz frequency range.

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Microwave Devices Based on Integrated HTS/ferroelectric Structures

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Theoretical and experimental results on low loss electrically tunable microwave devices based on integration of High Temperature Superconductors (HTS) with thin film and bulk single crystal ferroelectrics will be reported.

High quality epitaxial HTS films $YBa_2Cu_3O_{7-x}$ are grown on $SrTiO_3$ (STO) or $KTaO_3$ (KTO) ferroelectrics and their solid solutions using laser ablation, co-evaporation or sputtering techniques. Ferroelectric films are grown either by laser ablation or by sputtering. The thickness of the HTS films is typically 0.3-0.4 mm, and the thickness of ferroelectric films is in the range 0.2-1.0 mm.

Single crystalline bulk STO and KTO with HTS films are used in parallel-plate resonators. The resonators have circular (10 mm diameter) or square (1-2 mm side) shapes, the thickness in all cases is about 0.5 mm. These resonators are used for experimental investigation of the microwave loss mechanisms in ferroelectrics under applied electric fields. These experiments show the important role of the HTS/ferroelectric interfaces both on the dielectric hysteresis and microwave losses. The negative effects of the interfaces may be minimized by optimization of the deposition process of HTS film and proper choice of buffer layers between HTS films and ferroelectrics. The resonators have also been used to make electrically tuned band-pass and band-reject filters operating at frequencies 0.5-2 GHz at temperatures below the superconducting transition temperature of the HTS films.

Thin film HTS/ferroelectric structures are prepared on $LaAlO_3$ substrates by successive deposition of HTS films on ferroelectric films. HTS films are patterned using ion milling to form coplanar waveguides and lumped planar capacitors. Measurement of these structures is carried out both at low frequencies using standard capacitance meters and at microwave frequencies.

It is apparent from these measurements that the performance of thin film ferroelectrics is both quantitatively and qualitatively different from that of bulk materials. In contrast to bulk materials the thin ferroelectric films have higher dielectric losses. What is more important for practical applications is that these losses have a small frequency dependence in a wide band, from low frequencies to millimeterwaves and they decrease with applied DC electric field.

A considerable effort has been devoted to the modeling of HTS ferroelectric structures and the results will also be reported in this presentation.

Investigation of Characteristics of Different Thickness HTS Films at Microwaves

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This paper is devoted to the results of microwave and video pulse properties of different thickness HTS films. Such parameters of HTS films as surface resistance and critical current are impotent to design of controlling and limiting microwave devices based on S-N switching of superconducting film. The information of these parameters enable to evaluate a nonlinear parasitic phenomenon and handling power capability of devices based on HTS films. Investigations were carried out on a set of YBCO films with different thickness.

Films were deposited in the planar dc on-axis magnetron system in the atmosphere of pure oxygen. The r-cut single crystal Al_2O_3 substrate buffered by CeO_2 200 A layer was taken. The films were deposited at discharge current 600mA. The temperature of substrate holder was kept at 650^0C and was not varied with the film growth. The deposition time varied from 5 to 45 hours. The thickness of deposited films were measured by DEKTAK 3030 profilometer.

The structure quality of the grown films was studied by Rutherford Backscattering Spectroscopy and X-ray diffraction using the Gagerflex diffractometer Rigaku Dmax. The content of *c*- and *a*-oriented phase was evaluated from the relative intensity of (005) (*c*-orientation) and (200) (*a*-orientation) YBCO peaks. Two types of macrodefects were revealed by Scanning Electron Microscopy: second-phase inclusions and holes. Transmission Electron Microscopy showed that inclusions consist of CuO and YBCO (124) dielectric 100-200 nm islands.

Microwave surface resistance was measured at frequencies of 8.3GHz, using dielectric resonator based on TiO_2, and at the 60GHz, using cavity resonator with H_{011} mode. The value of critical current density was estimated basing on resonator quality factor variation.

Video pulse and microwave pulse films characteristics were investigated at 9.5GHz on devices employs the 3-element low pass filter. Critical currents were determined by the S-N switching of inductance element which constitute the microstrip line with different width. Accordingly this method enables us to measure dependencies of dc, video pulse and microwave pulse critical currents versus thickness and width of the HTS film. The preliminary results of investigations provide evidence for correctness of this method.

The main results of present work are follows :

1. The procedure to measure the microwave critical currents of HTS films was elaborated.
2. Investigation shows a good agreement of critical currents values measured at dc, video and microwave pulses.
3. The dependencies of critical currents and level of power handling versus thickness and width of HTS films were obtained.

Recent Advances on Superconducting Microstrip Patch Antennas

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A more accurate analysis and design for the HTc superconducting microstrip patch antennas is presented in this work, where we applied the Transverse Transmission Line (TTL) [1] method along with the Transmission Line Model [2]. Since the TTL is a full wave method and very much suitable on microwave components study, it gives accurate effective dielectric constant which contributes definitively to obtain high precision antenna parameters such as length, efficiency, bandwidth, quality factor, radiation patterns.

The HTS antenna shows a substantial improvement over an identical antenna made with normal metals, with a higher gain and radiation efficiency [3]-[4].

Considering the microstrip patch antenna, as a session of microstrip line of width *W*, a set of equations that represent the electromagnetic fields in the **x** and **z** direction as function of the electric and magnetic fields in the **y** transverse direction are obtained applying the TTL method. After various algebraic manipulations the general equations for the structure in the Fourier Transform Domain (FTD) are obtained. After the application of the boundary conditions, the Moment method is applied to eliminate the electric fields and to obtain the homogeneous matrix equation. The roots of this matrix are the attenuation constant (α) and phase constant (β). The effective dielectric constant is obtained from $\mathcal{E}_e = (\beta/k_0)^2$, where k_0 is the free space wave number.

The results, including efficiency, bandwidth, quality factor, radiation patterns and design parameters are shown, demonstrating the accuracy of the superconducting microstrip patch antenna parameters due to the dynamic method application. This work was supported by CNPq.

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Session H07
Thursday, July 16, PM 13:40-16:20
Room R02
Scattering by Complex Structures - Novel Applications I
Workshop on Complex Media and Measurement Techniques

Organisers : D. I. Kaklamani, G. S. Stamatakos

Chairs : D. I. Kaklamani, O. Breinbjerg

Applying the Method of Auxiliary Sources on Large Scale and Complex Structures

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During the last three decades the Method of Auxiliary Sources (MAS) has been studied extensively and numerous Electromagnetic structures have been computed while its accuracy was improbed. The MAS has been used to address problems related to radar cross section computations and analysis of electromagnetic compatibility, waveguiding and resonator structures as well as bioelectromagnetic applications [1,2,3].

The fundamental principle of MAS is based on the notion of representation of the scattered field by a superpostion of fundamental solutions of the related wave equation to the corresponding medium [4,5,6]. Placing the sources related to the fundamental solutions inside a homogenous media and requesting the validity of the associated boundary conditions on interfaces, the weighting coefficients of the sources are determined.

In applying the MAS to analyse the various electromagnetic structures experience in selecting the location of "Auxiliary Sources" is gained, thus leading into an optimization of the method. As already shown previously [2] the "Auxiliary Sources" are related to images of the exciting sources and their representation shows "Bright" regions within scatterers. In conventional MAS these regions are replaced by an effective Auxiliary Surface which embraces all sources. Moreover these regions are related to the concept of scattered field singularities and this concept is utilized in the following analysis. It is shown that the proper placement of "Auxiliary Sources" in space, enhances the efficiency of the MAS. Especially this is shown to be highly important in the case of tackling large size bodies when the object geometrical sizes are very large compared to wavelength.

Furthermore investigation of the scattered field singularities and their dependence to radiation frequency and scatterer shape provides highly useful results for the visualisation of targets observed at far field. At the conference a new visualization of the scattered field singularities technique, based on a holographic method, that has already given significant improvement on MAS implementaiton will be presented.

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Light Scattering and Light Confinement in Mesoscopic Systems

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We investigate the scattering of light in structures ranging from some nanometers to a few micrometers. This dimension range enables us to evidence different types of field-matter interactions. We mainly consider scatterers deposited on or embedded in a surface.

For small structures, we show that the interaction of light with matter can lead to localized electromagnetic fields that are confined to the close vicinity of the scatterer. This confinement is related to evanescent field components that are produced during the scattering process. This phenomenon is mainly frequency independent but is strongly influenced by the polarization of the incident field. These evanescent fields perfectly reproduce the shape of the scatterer, and can therefore be used to obtain extremely high resolution optical images. Such effects are used experimentally in scanning near field optical microscopy to achieve a resolution much better than the diffraction limit.

For larger structures, we show that the interplay of light with a collection of scatterers can also lead to light confinement. In this case, the electromagnetic fields are not localized on the scatterer themselves but between them. This effect is now strongly frequency dependent and can be interpreted as the manifestation of a pseudo photonic bandgap structure in the system under study.

Finally, we investigate the transition from the near field to the far field, when the observation distance to the scattering system is increased. Different types of distance dependences are evidenced and their implications for pratical experiments discussed.

Calculation of the Radar-Cross-Section (RCS) of Complex Radar Targets using the Physical Optics Approximation

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The calculation of the RCS of realistic radar targets, such as ships and airplanes, is considered in this paper, by using, as a first approximation, the well-known Physical Optics (P.O.) approach. The surface of the complex radar target is assumed to have infinite conductivity, while both cases of linearly and circularly polarized incident electromagnetic (EM) waves are considered.

The method is based on the division of the scatterer's surface into a large number of plane triangles or parallelograms, on each of which the P.O. electric current is calculated. The far-zone backscattered electric field and RCS is then calculated using the superposition principle and standard techniques. This involves calculation of integrals of standard complex phase functions over the surface of the triangles or parallelepipeds, which yield closed-form analytical expressions with possible singularities present (case of triangular domain of integration) or not present (case of parallelograms). The proposed method is currently implemented for usual and realistic radar target geometries. Future work will involve use of complementary electromagnetic techniques for the RCS calculation, such as multiple scattering geometrical optics and method of moments techniques, as well as consideration of the RCS reduction problem. Finally, for the case of ships as radar targets, the effect of the presence of the sea surface on the RCS calculation will be taken into account using image theory.

Comparison of the UTD and EFIE Method for the Analysis of Electrically Large Reflectors

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The calculation of the electromagnetic fields, reflected and diffracted from electrically large reflectors, requires the selection of an adequate analysis method. The existing methods can generally be divided into asymptotic and exact methods, whereas the accuracy of the asymptotic methods and the calculation time of the numerically solved exact methods mainly limit its applicability. An alternative solution is the combination of an asymptotic and an exact method, the so called hybrid method, which is also under investigation.

Within this paper the electromagnetic fields from reflectors with different rim contours are calculated with both an asymptotic and an exact calculation method. The used calculation methods are the combination of the Geometrical Optics (GO) and the Uniform Geometrical Theory of Diffraction (UTD) as well as the solution of the Electric Field Integral Equation (EFIE) with the Methods of Moments (MoM). The GO/UTD analyses are performed with an analysis tool, developed at the Fachhochschule Muenchen, and the EFIE/MoM analyses with the field analysis tool CONCEPT, developed at the Technical University of Hamburg-Harburg, Germany.

The considered reflector geometries are rectangular reflectors with different triangular sections added to the sides of the reflectors. The dimensions of the reflectors are varied up to a maximum length of approximately 20 wavelengths. The analyses will be carried out in the near and far field for horizontal and vertical cuts. A variation of parameters is related to the number and length of the triangular sections. These parameters mainly determine the influence of the edge and corner diffracted fields resulting from the GO/UTD analyses. The field contributions itself determine the accuracy of the asymptotic method.

The field analysis results of both calculation methods will be presented and compared concerning the amplitude and phase pattern, the half-power bandwiths, the 1st and 2nd sidelobe levels and the calculation times. The paper will be closed with a final statement about the applicability and accuracy of the GO/UTD method for electrically large reflectors.

Uniform High Frequency Description of Single, Doubly and Vertex Diffracted Ray Contributions to the Currents on a Polygonal Plate

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High-frequency expressions for the electric currents induced on a polygonal perfectly conducting plate illuminated by a plane wave are derived in this paper, on the basis of the Incremental Theory of Diffraction (ITD) [1]-[3]. The application of this theory in deriving currents is particularly attractive, since the ITD diffraction coefficients satisfy the boundary conditions of their pertinent tangent canonical wedge, so that they ensure a reasonable accuracy of the estimated currents. These currents are represented in terms of the the Physical Optics (PO) current plus the current induced by singly and doubly diffracted rays at each edge of the plate. For each of this two type of contributions, additional currents associated to vertex diffracted rays are introduced, that provide a uniform description of the total currents at the shadow boundary lines of singly and doubly diffracted rays, respectively. The problem is formulated as follows. First, the polygonal plate is considered as superposition of canonical plane angular sectors with straight infinite edges. Next, incremental diffraction coefficients based on ITD are distributed on the semi-infinite edges of the plane angular sector. Finally, a uniform asymptotic evaluation of the integrals on the semi-infinite edges are carried out, retaining orders up to kr, where r is the distance from the tip. The currents found by this procedure are applied to a polygonal plate taking care to avoid superposition of contributions arising from the share of the infinite angular sector faces which model the finite plate. For this particular case of infinitely thin plates, the final solution also satisfy the edge conditions asymptotically far from verteces. Different kind of tests are presented to validate the solution. First, a comparison with the exact currents of a plane angular sector [4] will show that our formulation provides satisfactory results even at half a wavelength from the verteces. Furthermore, a succesful comparison with the currents found by the Method of Moments and with the radar cross section predicted by other methods [5][6] will be presented.

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A Comparative Study of the Plane Wave Scattering by Perfectly Conducting Strip Gratings and Unidirectionally Conducting Surfaces

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Strip gratings are employed in antenna technique because of their polarisation selective capability which enables for example dual-polarised reflector antenna systems with frequency re-use and hence high transmission capacity. The analysis of the scattering by a strip grating simplifies considerably if the grating can be accurately modelled by a unidirectionally conducting surface since the exact analytical solution and thus high-frequency asymptotic solutions are available for the unidirectionally conducting half-plane. The accuracy of modelling the strip grating by a unidirectionally conducting surface depends upon several parameters such as the strip width and period of the strip grating as well as the frequency, polarisation and direction of propagation of the incident field. In this study we investigate the dependence of the accuracy on these parameters for plane wave scattering by two structures, the strip grating plane and the strip grating strip.

The infinite strip grating plane is modelled by an infinite undirectionally conducting plane. The scattering analysis of the former employs the technique reported in [M.Ando and K. Takei, "Reflection and transmission coefficients of a thin strip grating for antenna application", *IEEE Trans. Antennas Propagat.* vol. 35, no. 4, pp. 367-371, April 1987] while the analysis of the latter follows from simple plane wave theory. Ando and Takei assume that only the zero'th-order plane wave of the scattered far-field exists and they derive the reflection coefficient for this. We derive the reflection coefficient for the unidirectionally conducting plane and compare the two coefficients for varying values of the above-mentioned parameters. This enables the identification of that region in the parameter space wherein the two reflection coefficients differ by less than a given value, e.g., 0.5 dB.

The strip grating strip, a rectangle of finite width and infinite length cut out from the strip grating plane, is modelled by a unidirectionally conducting strip. The scattering by these structures comprises not only the reflection from the surface but also the diffraction from the edges including surface wave excitation and diffraction. The scattering analysis for the strip grating strip is based on the electric field integral equation with the periodic structure Green's function. This integral equation, which extends over one period of the strip grating strip, is solved by the method of moment with the induced surface current being decomposed along non-orthogonal directions and the Green's function evaluation being accelerated by use of the Poisson transformation. For the unidirectionally conducting strip the analysis is also based on the electric field integral equation but now employing the free-space Green's function and applied to only that component of the electric field which is parallel to the direction of conductivity. In this case the integral equation extends over the cross section of the unidirectionally conducting strip. For both structures the integral equations lead to the induced surface currents from which the scattered far-fields are calculated. These far-fields are then compared for varying parameter values; e.g. with the strip grating period ranging between 0.1l and 0.5l (l being the wavelength) and the strip width ranging between 0.1 and 0.9 of the period.

The comparative study undertaken here shows that under certain conditions the unidirectionally conducting surface constitutes an accurate model of the strip grating. The analysis techniques available for the former [O. Breinbjerg, M.V. Jensen, M. Lumholt, "Scattering by the unidirectionally conducting strip -comparison of different techniques", *Proceedings of the 1997 North American Radio Science Meeting*, July 13-18, 1997, Montreal, Canada, p. 721] can thus be applied to simplify the scattering analysis.

Extension of the Maliuzhinets Method to the Scattering by Anisotropic Impedance Wedges Illuminated at Oblique Incidence

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The scattering by non-perfectly conducting bodies has received an increasing attention in the context of asymptotic techniques, due to the wider and wider use of composite materials. For instance, approximate impedance boundary conditions (IBC's) have been extensively applied in the analysis of the field scattered from non-penetrable material structures. A spectral method which allows us to derive a rigorous integral representation for the total field in the presence of an isotropic impedance wedge illuminated at normal incidence was proposed by Maliuzhinets in [G.D. Maliuzhinets, "Excitation, reflection and emission of surface waves from a wedge with given face impedances," *Sov. Phys. Dokl.*, Vol. 3, 1958]. This solution was later on extended to the oblique incidence case for specific wedge configurations, again when the wedge faces are characterized by isotropic IBC's [R.G. Rojas, "Electromagnetic diffraction of an obliquely incident plane wave field by a wedge with impedance faces," *IEEE Trans. Antennas Propagat.*, Vol. 36, No. 7, July 1988]. More recently, by resorting to the Maliuzhinets technique, three-dimensional rigorous spectral solutions have been derived for wedges with anisotropic impedance faces [G. Manara, P. Nepa, G. Pelosi, "EM scattering from anisotropic impedance wedges illuminated at oblique incidence. The case of artificially hard and soft boundary conditions," *Electromagnetics*, Vol. 18, No. 3, May-June 1998]. The class of anisotropic IBC's considered is characterized by tensor impedances exhibiting a vanishing surface impedance in a principal anisotropy direction. They can be usefully applied to analyze the scattering by edges in artificially hard and soft surfaces [P.S. Kildal, "Artificially soft and hard surfaces in electromagnetics," *IEEE Trans. Antennas Propagat.*, Vol. 38, No. 10, Oct. 1990]. We note that computational costs for evaluating the fields in these more complex configurations are the same as those for the corresponding isotropic cases, since the rigorous spectral representations contain simple trigonometric terms and the well known Maliuzhinets special function. The properties of this latter function have been widely described in the literature and accurate analytical approximations proposed.

This communication is intended to provide some details on the application of the Maliuzhinets method to the analysis of the scattering from anisotropic impedance wedges illuminated at oblique incidence. First, we review some three-dimensional solutions recently derived, also describing further developments of the work. Particular attention is devoted to analyze the phenomenon of surface wave excitation at the edge of the wedge and their propagation along the wedge faces. Then, samples of numerical results will be shown and compared with data obtained by reference solutions in order to demonstrate the accuracy of the asymptotic evaluations performed.

Session H08
Thursday, July 16, PM 16:20-18:20
Room R02
Scattering by Complex Structures - Novel Applications II
Workshop on Complex Media and Measurement Techniques

Organisers : G. S. Stamatakos, D. I. Kaklamani

Chairs : G. S. Stamatakos, K. Kyriaki

The Cylindrical Localized Approximation to Speed Up Computations in the Generalized Lorenz-Mie Theory for Cylinders

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The general theory of interaction between an arbitrary shaped beam and an infinite cylinder has been recently developed [1]. Under its more general version, the theory has to be expressed in terms of distributions, in particular if the illuminating beam is described in the so-called Davis formalism [2] ,[3].

By analogy to a similar theory, called generalized Lorenz-Mie theory (GLMT) when the scatterer is a sphere [4], [5], the above theory is called GLMT for cylinders. The approach in terms of distributions is equivalent to a plane wave spectrum approach [6] although, in its more general version, the plane wave spectrum approach also may have to deal with distributions.

The plane wave spectrum approach however is in suitable form to develop a so-called cylindrical localized approximation which is very akin, in its spirit to the localized approximation which has been previously developed in the case of spheres [7]. This approximation allows one to speed up numerical computations in the framework of the theory.

This presentation will introduce the above approximation in the case of arbitrary orientation and arbitrary location of the cylinder, from which a previous case of perpendicular on-axis illumination may be recovered [8].

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The Invisible Part of an Object or Source Distribution. Maxwell and Radiative Transfer Theory of Objects and Sources Generating Zero Intensity Outside the Distribution

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The field inside a finite current-source distribution contains two components: (i) The non-radiating component which satisfies the Wolf boundary conditions, (the field and its normal derivative are zero on the boundary of the source volume); (ii) The radiating component which is obtained by subtracting the nonradiating component from the total field inside the source volume.

This nonradiating component can be expressed in terms of a set of discrete modes of the inhomogeneous vector wave equation, which have been shown to be complete inside the volume but not on its boundary.

The nonradiating component is obtained by projecting the total field on the space spanned by these inhomogeneous modes. The remaining part corresponds to the radiating component which is usually observed outside the source volume.

The same ideas are applied to fields satisfying the equation of radiative transfer. The radiance- or the intensity distributions inside a source or a scattering object contain a non-radiating component, leading to zero radiance- or intensity outside the source- or scattering object.

We introduce a novel set of modes of the inhomogeneous equation of radiative transfer, into which the non-radiating component of the radiance can be expanded. A similar set is also introduced for the intensity density inside the object or source.

The present formalism enables us to make explicit which part of the current-, source-, or object distribution can be retrieved and thus to assess the degree of uniqueness.

Integral Equation Solution to the Elastic Scattering of Light by Systems of Red Blood Cells

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The problem of the elastic scattering of light by certain systems of oriented or aggregated triaxial dielectric ellipsoids of complex index of refraction has been rigorously solved by applying the general method of integral equations in conjunction with the method of moments (MoM). The systems under consideration can simulate red blood cells (RBCs) inside an operating ektacytometer or in a flow cytometer, red blood cell rouleaux or even non biological particles such as atmospheric aerosol, interstellar dust etc.

A general triaxial dielectric ellipsoid of complex index of refraction is used as the physical model of a normal, a mechanically deformed or a pathological RBC (e.g an elliptocyte). It is also used as the physical model of a RBC constituting part of a RBC aggregate.

The exact problems that have been solved in the course of the present work are the following.

1. Plane wave scattering by a single dielectric ellipsoid with arbitrary position and orientation in a given cartesian coordinate system.
2. Plane wave scattering by an oriented monodisperse system of non interacting dielectric ellipsoids.
3. Plane wave scattering by a system of two electromagnetically coupled dielectric ellipsoids.
4. Plane wave scattering by a linear chain of weakly coupled dielectric ellipsoids.

The analysis in each case considered has been based on the formulation of an appropriate Lippman-Schwinger integral equation for the electric field. The scattering amplitude has been deduced using the limit of the same equation as the distance of the point of observation from the center of the system of scatterers tends to infinity. Since each integral equation under consideration contains a number of singular kernels, it has been transformed into a set of nonsingular integral equations for the angular Fourier transform of the internal field of each scatterer. The latter equations have been solved by reducing them by quadrature into a matrix equation. The resulting solutions have been used for the calculation of the scattering amplitude.

Furthermore, a Monte Carlo simulation has been developed for case '2' in order to reproduce the diffraction pattern of aligned ellipsoids. Thus, a novel check of the electromagnetic basis of ektacytometry, an optical technique for quantifying RBC deformability, has been provided.

Serial and shared memory parallel computer programs implementing the previous treatments have been developed. Various convergence and accuracy tests, including comparison with Mie theory for spherical erythrocytes, have been conceived and applied in order to ensure the validity of all simulations for the RBC cases.

Due to the relatively high computing cost of the models developed, numerical results have been restricted to the near forward angular region ($\pm 25^o$ around the direction of wave incidence). However, this region has proven to be of the most importance to many diagnostic applications. Sample calculations for incident wavelenth λ =0.633 μm have been performed.

The inverse scattering problem for dielectric bodies - An Application to Shape and Refractive Index Analyzer

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The problem of recovering the shape of a body from the particular way it disturbs the propagation of a time-harmonic incident electromagnetic wave, it is one of the most important problems of inverse scattering theory. In this work the inverse problem for dielectric bodies is considered in R^3. We use a system of uniquely solvable, integral equations which describes the scattering process in order to compute the far-field amplitudes. Continuity dependence of the far-field patterns upon the shape of the scatterer is proved to stabilize the inverse problem. An optimization scheme is proposed to derive solutions incorporating a priori information about the shape and size of the scatterer. A fast inverse algorithm, based on the mathematical consideration of the inverse problem is proposed. More precisely, fast and reliable characterization of the shape and the refractive index is achieved by comparing certain properly selected characteristics of the scattered light pattern with the corresponding theoretical values. The whole procedure is not computationally expensive. A use of the inverse algorithm has been done in a biological application concerning the identification of the shape and refractive index of red blood cells and bacteria.

A Recent Advance in Light-Scattering Theory : the Development of a Rigorous and Complete Solution to Multiparticle-Scattering Problems

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Scattering by small particles is an important subject in nearly all scientific disciplines. For a long time, exact scattering theories have been available only for single isolated spherical and spheroidal particles and for single and multiple infinitely long circular cylinders. Mie theory for single homogeneous and isotropic spheres has been in extensive use for an entire century. Many particles in nature, however, do not have high axial symmetry nor are they isolated. For example, aerosols and cosmic dust, are often believed to have a fluffy aggregate structure. The simplest configuration of aggregated particles is probably the aggregate of spheres. The theoretical study of light scattering by interacting spheres has been an active area of research during the last few decades.

Recently, the major fundamental theoretical and numerical issues involved in the development of a rigorous multisphere-scattering theory have been clarified, and the analytical solution to the multisphere-scattering problems has been complete. Mie scattering is the simplest special case of this exact multiple scattering theory. The major components of the theory include: (1) analytical expressions and numerical techniques for the efficient and accurate evaluation of the Wigner 3jm symbol, the Gaunt coefficient, and the vector translational addition coefficients required by the vector addition theorems for spherical harmonics, (2) the solution of the partial scattering coefficients of all individual spheres from the generalization of the Mie theory, (3) an asymptotic form of the vector addition theorems in the far zone and an asymptotic single-field representation of the total scattered far-field consisting of all the partial scattered fields expanded in individual constituent-centered reference systems, and (4) the rigorous analytical expressions for all total and differential scattering properties of an arbitrary ensemble of small particles that may be either spherical or nonspherical, including all the elements of the amplitude scattering matrix and thus the Mueller matrix, the four efficiencies for extinction, scattering, absorption, and radiation pressure, as well as the asymmetry parameter.

Numerical and experimental tests of the theory have been so far uniformly successful. A large set of microwave analog scattering measurements for various aggregates of spheres, including some large ones consisting of a few hundreds of spheres, is used for a scrutiny of the theory. This set of laboratory measurements contains angular distribution of the scattered intensities for fixed and random orientations, polarization, extinction, scattering, and absorption cross-sections, asymmetry parameter, forward scattering property, and others. The theoretical predictions agree favorably with experimental data without exception.

The multisphere-scattering theory has a wide range of practical applications in a variety of scientific areas. For example, the optical and physical properties of interstellar dust have been a subject of astronomical research and debate for over sixty years. Astronomers have extensively investigated interstellar extinction and polarization, diffuse scattering, and interstellar reddening, based on light-scattering models. The development of the multiparticle-scattering theory paves the way for a new approach to modeling complex aggregated particles and has opened up a new window to look into the radiative and dynamical behavior of interstellar and circumstellar dust.

Optical Characterization of Complex Structures Formed in Combustion Systems

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Combustion is one of the most impressive phenomena, present in most natural events and human activities, where physics and chemistry strongly interact. Optical techniques offer a powerful diagnostic methodology to study the complex mechanisms that govern the combustion process. The aim is to achieve greater comprehension of the involved processes in order to design more efficient combustors which respect the environment. This paper will discuss the application of light scattering, absorption and fluorescence techniques to study two specific problems: the characterization of vaporizing/burning fuel droplets and the formation of soot.

In recent years, many optical methods, based on the measurements of the properties of elastically scattered light have been developed to characterize single droplets inside sprays. The Lorenz-Mie theory, which is strictly valid only for the scattering by homogeneous spheres, is commonly utilized as the theoretical bases in the reduction of the experimental data from these techniques. However, droplets in real sprays are usually non-homogeneous. The heat and mass transfer process will establish a radial profile of temperature and species, and therefore of refractive index, inside the droplets. In these cases the Lorenz-Mie theory is not adequate and more sophisticated scattering models must be employed. In order to compute the light scattering by radially inhomogeneous droplets, the finely stratified sphere model has been developed. This algorithm allows the computation of the scattering by stratified spheres with a high number of layers (typically thousands or tens of thousands). The scattering by spheres with any continuous profile can be calculated with very good accuracy using the model with a sufficient number of layers. In the paper, the relevant features present in the light scattering angular patterns relative to radially inhomogeneous spheres will be outlined. Thus the possibility to characterize, by light scattering methods, droplets in practical reactive systems will be critically discussed.

In real combustion systems (specially in turbine, Diesel engines and light oil burners) soot represents one of the exhaust products of major impact on the environment and on the public health. The formation of soot starts with the pyrolysis of the fuel in the gaseous phase at high temperature. Rearrangement of the pyrolysis product in larger molecular structures, chemical abstraction, condensation, surface growth and agglomeration complete the transition towards solid particles. The final result is a solid carbonaceous agglomerate (the soot particle) composed of tens of primary spherules with a diameter in the range 10-40 nm. The time scale of the whole process is few hundreds of microsecond. In the paper, the application of optical methods to study the soot formation mechanism will be reported. The intermediate molecular species formed in the early stages of the process have been followed by high speed absorption and fluorescence spectroscopy, in the range 200 nm - 800 nm, and by time resolved light scattering. Soot growth and agglomeration have been followed by light scattering/extinction techniques. In addition, the diameter and the mean number of the primary spherules in the aggregates have been inferred by the measurements of light extinction and scattering at different angles.

J. I. P. R. 4 - Session I06
Thursday, July 16, PM 13:40-15:20
Room 200
Polarimetric Diffraction and Scattering and Applications

Organiser : F. Molinet

Chair : F. Molinet

Physical Diffraction Phenomena Versus Abstract Mathematical Concepts in Radar Polarimetry

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This paper gives an overview on the polarization dependance in Geometrical and Physical Optics, Geometrical Theory of Diffraction and Physical Theory of Diffraction augmented by the asymptotic current method. Both monostatic and bistatic diffractions are considered on perfectly conducting objects.

The primary objective of this paper is to discuss the relationship between the geometrical characteristics of a target and its optimal polarimetric signatures.

The author has shown in previous publications [1] that the monostatic Sinclair scattering matrix corresponding to N single reflection points on a smooth target can be decomposed into a symetric target (sphere like target) and a non symetric target (diplane), the latter being of order $^1/k$ compared to the main term of the symetric target, where k is the wave number. This procedure has later on be extended to a target with edges where a similar decomposition has been performed. Multiple interactions comprizing double and triple bounce reflections, single reflections associated with single edge diffraction have been analysed [2]. It has been shown that when doubly-reflected waves are absent, edge diffraction becomes the dominant effect on polarization. Furthermore, when multiple interactions involving edge diffraction occur, a third component, in addition to the sphere and diplane components, corresponding to a right or left wound helix, appears in the decomposition of the Sinclair scattering matrix. Such a decomposition together with the behavior of the components with frequency, have been exploited to filter out the contributions corresponding to different scattering phenomena on a missile-shaped target and to construct separate polarimetric ISAR images showing the scattering centers associated with each phenomenon.

After having presented a synthesis on these results, with typical applications to inverse scattering problems, the author shows some relationships between the physical approach and some abstract mathematical concepts in Radar Polarimetry. Especially, optimal polarimetric signatures are correlated with scattering features of more complex shapes, the scattering matrices of which are determined by the asymptotic current method [3].

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Prediction of In-Band Microstrip Antennas Array RCS

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Microstrip antennas arrays are commonly in use nowadays, particularly in radar applications. Because of the need of high performances, in terms of purety polarisation, directivity, low sidelobes levels etc... to realise the missions for which the array has been developped, its RCS can become a predominant level.

The purpose of this paper concerns the microstrip antennas arrays RCS, taking into account the reflections in the feed network (i.e the load). The planar array is composed of 16 x 16 elements (Coupled-Patches Aperture) with parallel corporate feed networks (216 unbalanced Wilkinson and 36 unbalanced hybrid ring power dividers) generating a 12° sector beam pattern with low sidelobes levels (under -25 dB in both main planes) in 25 % bandwidth around 4 GHz [1].

The basic equation of antenna scattering used by severals authors [2], [3] is the sum of two terms : the "structural mode" and the "antenna mode". In the presence of a large array, the structural mode is mainly due to edge effects and generally small compared to other component in rand, therefore only the antenna mode is considered.

The analysis method derived from [4] is extended to the precise case where each power divider is represented by its S-parameters matrix and is assumed to be reciprocal.

Finally the theoritical results are compared with measurements and the characteristics of array RCS are presented.

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Electromagnetic Analysis of Dual Polarized Wide Band Antennas and Arrays

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Future radar systems have to insure multi-task working, with wider bands of frequencies to cover. These systems are submited to crowding and cost constraints, leading to a compromise for the realization.

Nowadays, 2D or 3D electromagnetic precise simulations of antennas and also of arrays with parallel computer, for a good prevision of performances, are possible.

The purpose of the paper is, first to present briefly an analysis tool issued from integral equations treatment, adapted to the study of antennas and arrays. The precision of simulations is confirmed by several experimental results. The analysis gives the current distributions on radiating surfaces for any frequency, the input impedance of antennas or a coupling matrix of an array; the insertion of loads is taken in account. The radiated fields providing data bases for polarimetric applications are computed in all space. The software allows the modelization of arbitrary shape antenna , including printed antennas on finite substrate, in the limits of computer possibilities. For a polarimetric investigation dual polarized antennas are very interesting. The first model presented, called "star" antenna, have a behavior independent of frequency, approaching the octave.
Others interesting characteristics for radar applications, are the reduced size of the sources, the position of the phasis center identical for the two polarizations independent of the frequency, and the presence of a ground plane behind the antennas. The analysis tool suggests also new source designs like an antenna with radiation patterns regularization and a dual polarized multi octave antenna.

The method has also contributed to the conception of wide band arrays covering a frequency band near the octave. Compromise solutions have been obtained, with regards of side lobes levels and mutual couplings values. Feeding, coupling effects and loads influence on a dual polarized array working from 6 to 10 GHz have been studied with DGA/ DRET support, and theoretical radiation patterns data base, has been transmitted to SEI Laboratory of the University of Nantes for polarimetric investigations.
Others dual polarized arrays have been realized in the band 2 to 4 GHz, with C.E.A. support. The theory provides a good agreement for radiations patterns, especially fo arrays side lobes levels.

Finally, this software who have been parallized with the help of the IRISA of Rennes, operational on CRAY/T3E (CNRS/IDRIS) allows now a performant analysis for tri dimensionnal antennas and large arrays.

Particle Shape Determination from Polarization Fluctuations of Scattered Radiation

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The probability density function (pdf) for the amplitude of polarized radiation which has been scattered by a spheroidal particle has general features which relate to the morphology of the particle, such as it's size and shape. These features are sufficiently characteristic for the inverse problem of particle shape determination to addressed.

In the case of a particle whose size is small compared to wavelength, a dipole model may be applied. The polarizability is represented by a diagonal tensor, whose elements are related to the semi-major and -minor axes of the particle, and analytical expressions for the amplitude functions of the polarized scattered radiation are obtained. These expressions are functions of the particle orientation and by taking suitable averages over the Euler angles enables the pdf of the amplitude fluctuations to be calculated in closed form. It is found that the pdf's for radiation measured in the co-polarized state have forms whose features relate to the aspect ratio of the particle, and hence enable oblate and prolate shaped particle to be distinguished from one another.

For larger particles the dipole model is inapplicable, but the principles for finding the amplitude fluctuations are identical. The scattered amplitudes can be found for particles of spheroidal shape and arbitrary size using the T-Matrix method. A Monte-Carlo technique is then employed to create numerous realisations for the particle orientations and hence produce pdfs for the various polarization states as before. These pdfs have a richer structure than that for the dipole model, especially as the particle size increases through the resonance region. Nevertheless, general features are evident in the form of the pdf's and we discuss how these features relate to particle size, shape and refractive index when these particles are presented singly and in fluctuating ensembles. The possibility of measuring such fluctuations under experimental conditions will be addressed.

J. I. P. R. 4 - Session I07
Thursday, July 16, PM 15:40-17:20
Room 200
PLENARY SESSION AND PANEL DISCUSSION

Organiser : W.M. Boerner
Chairman : F. Molinet

INVITED KEYNOTE ADDRESS

What Do Mathematics Afford to Inverse Electromagnetic Scattering ?

A Tribute to Kleinman's Accomplishments

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It is known that large or complicated targets producing small cross sections for most aspects or frequencies cannot be obtained simply as the mathematical solution of an "Inverse Electromagnetic Problem". Mathematics proved their efficiency for the following purposes in restricted problems of identification or synthesis :
- constructive purpose : mathematics give methods either for optimizing fits or for minimizing cross sections
- predictive purpose : mathematics give conditions that lead to non uniqueness of solutions : the results can be used either to predict stealth targets or to suggest further ways of collecting data, which suppress the nonuniqueness.
- analytic purpose : for instance, - mathematics give ways to understand why resolution is limited
- synthetic purpose - mathematics show links between propagation or scattering problems.

However, only physics is able to predict these links, or to improve resolution, or simply to define the true mathematical problems. In the case of polarimetry, for instance, mathematical analyses of the direct problem are available but those of real world inverse problems are very few. The present paper yields a terse survey of recent incursions of mathematics in the science of electromagnetic scattering. Throughout many parts of it, results of our late colleague R. Kleinman do appear as a guide, so that the lecture is a tribute for the man and his work.

Session J04
Thursday, July 16, PM 13:40-16:20
Room 450
Scattering from Natural Bare Soils

Organiser : F. Mattia
Chairs : F. Mattia, T. Le Toan

New Approaches to the Observation and Modelling of the Radar Backscatter from Bare Soil Surfaces

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Since the launch of ERS-1 in 1991 a number of studies have produced experimental results relating the observed radar backscatter to the soil moisture conditions prevalent at the time of the image acquisition. However at the same time these empirical results appear site and time dependent. The lack of a full understanding of the phenomena involved has hindered the development of widely applicable direct models, which in turn are a prerequisite to the development of inversion algorithms permitting an effective use of SAR data. For the backscattering from bare soil surfaces, a variety of direct models using different approximations to solve Maxwell's equations have been used. In most cases these models assume that the surface roughness is both stationary and possesses a single intrinsic scale, implying that it can be described that through only two parameters : standard deviation in height and correlation length. However, in recent work, this description has been found to be inadequate in the representation of most natural soil surfaces. Thus current modelling techniques would benefit from a more realistic description of natural soil surfaces, in addition to better approximations to solve Maxwell's equations.

This paper presents the results of a study conducted in the past two years by research teams having both experimental and theoretical backgrounds. The study makes use of a large data base of detailed measurements of surface roughness conditions, provided by ESA and other team members, in order to investigate novel methods in the characterisation of surface roughness for electromagnetic scattering. The improved models are tested and validated using both numerical methods for a limited number of test cases and experimentally, making use of selected experimental radar and ground data acquired over a wide range of surface conditions. The possibilities of inversion are assessed for different SAR measurements, with a particular attention paid to the use of ERS, RADARSAT and ENVISAT data.

The paper will present the objectives, approach, the work completed and a summary of the main results.

Multiscale Surface Roughness of Natural Bare Soil

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The nowadays in remote sensing commonly used surface roughness description based on single scale rms height and correlation length does not characterise all the properties of natural surfaces that are relevant for scattering. A new method is to describe the surface with the inclination angle obtained by linear regression of the surface and multiscale surface roughness on top of this inclination. The main idea of the multiscale surface roughness description is that the surface roughness is thought to be a superposition of various wavelengths.

The roughness components included can 1) cover a semi-infinite band starting from zero or 2) consist of one or more infinite wavelength bands. It is also possible to combine separate distinct periods or period bands with random roughness of various sizes. The surface roughness description of seemingly periodic profiles really turned out to be more characteristic, when the distinct period (or periods) was removed from the profiles and the remaining part was treated as random roughness.

The only assumptions of the multiscale autocorrelation function approach are, that the logarithm of the rms height depends linearly on the logarithm of the measured distance and the correlation length depends linearly on the measured distance. The multiscale autocorrelation functions are obtained as integrals of normal single scale autocorrelation functions corresponding to individual wavelengths of various wavelength bands. The multiscale autocorrelation functions depend then on the shape of the observed individual autocorrelation functions and the parameter b that describes the distance dependence of the rms height. The multiscale autocorrelation approach is more a statistically justified treatment based on experimental results than a pure theoretical method.

In practice the basic assumptions of the multiscale autocorrelation method seem to be well justified. The assumed linear regressions turned out to have very high correlation coefficients: The median values for about 5990 profiles of a ploughed field were better than 0.99 (for rms height) and 0.98 (for correlation length). The multiscale behaviour of a ploughed field was evident upto the longest distances tested (30 m). Also the multiscale autocorrelation shapes turned out to correspond to the experimental ones very well.

For the time being analytic electromagnetic models typically make use of the assumption of a stationary gaussian surface. Although this is a natural starting point for randomly rough infinite surfaces, it is not always justified in the case of bare soil fields. Especially finite pixels of anisotropic surfaces, such as ploughed fields, can not automatically be assumed to be even close to stationary gaussian surfaces. The phase shift and long wavelength (easily larger than the pixel) close to the row direction complicates the measurements and description of distinctly periodic surfaces, because different pixels will really differ from each other from the point of view of surface roughness. Therefore it is important, that for modelling purposes one describes pixel size surfaces, not the ideal infinite surface. In principle the correlation length increases radically close to the row direction. In practice this is limited by the random component of the roughness of the surface so that actually the correlation length usually decreased close to row direction. The rms height of an infinite periodical surface is independent of the direction, but for finite periodic surfaces its distance dependence turned out to be stronger in the perpendicular direction.

Measuring Roughness at Pixel Scales : From 1 Meter to 25 Meter Profiles

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Historically the validation of both asymptotic and numerical radar scattering models for natural surfaces has been carried out by feeding such models with observed soil moisture and roughness information and comparing the results of the calculation with backscatter observation. Soil roughness information has traditionally been expressed in terms of vertical roughness (height standard deviation) and horizontal roughness components (correlation length). One of the main problems in such validation exercises has been the lack of stationarity in the derived roughness characteristics, which tend to vary from one profile to the next, especially so in the case of the correlation length. A second and related problem has been the dependence of the derived roughness characteristics on the length of the profile used which is typical of multi-scale surfaces.

In view of these problems a number of alternative roughness characterisation approaches, such as fractal dimension or multi-scale autocorrelation function, been suggested. However a major problem in the validation of these theories, which are intrinsically multi-scale, has been the limited length, usually of the order of one or two metres, over which roughness information has been collected to date. In fact little is known about the shape of the roughness power spectrum at spatial scales between 1m and the pixel size and assumptions have to be made. For instance the fractal description predicts a 1/f power spectrum shape so that the undulations in the terrain at lower frequencies have a much larger amplitude than at the higher spatial frequencies. As a first step in addressing this problem, a laser profiler capable of measuring long profiles up pixel scale (approximately 30 metres) has been built and a series of measurements performed in agricultural fields. The work was carried out within the framework of the contract ESA-ESTEC 12008/97/NL/NB(SC).

With this behind-the-scenes motivation in mind the aim of the paper is to present first of the all the characteristics of the laser profiling instrument and its mode of operation, followed by details about the measurement campaign itself. Finally the initial results from the ground-truth measurement campaign will be presented and commented upon.

On the Backscattering from Multiscale Rough Surface

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Backscattering measurements conducted in anechoic chambers on artificial random surfaces built according to a specific roughness description have generally shown a good agreement with theoretical results. A large variety of Gaussian stationary rough surfaces having different ACF as well as different s and l parameters have been tested. Measured backscattering values and theoretical results are in agreement within the range of validity of e.m. asymptotic models.

However, in natural conditions, the agreement between experimental measures and theoretical backscattering derived from simulation of asymptotic models is usually poor. The weak point in remote sensing applications of the e.m. models appears at present due to the inadequate description and measurement of natural surfaces rather than to a failure of e.m. models. In natural conditions, most bare soil surfaces exhibit a large spatial variation. Different surface profiles acquired in an apparently homogeneous field can give large range of s and l. The most critical point is the correlation functions which are largely variable.

In fact, many previous works dealing with mathematical surface description in different fields of application and in different spatial scales have often concluded that natural surfaces are usually better described as random fractals (i.e. multiscale random processes) than as stationary processes.

Even though, the problem of assessing to what extend natural roughness can be considered as a self affine random process is still an open question. The purpose of this paper is to investigate the effect of a multiscale surface description on backscattering response obtained by using asymptotic e.m. models.

In this study, natural roughness is modelled as 1/f random process and a new approach to describe surface roughness is proposed. The method exploits a Karhunen-Loeve expansion of 1/f processes in terms of orthonormal wavelet bases. The approach is adapted to remote sensing purposes by introducing thresholds for the finest and coarsest spatial scale of e.m. interest. In fact, the two thresholds are related to the smallest detail and to the largest surface spatial scale which may affect an impinging e.m. wave, respectivelty.

The obtained random process aimed at modeling surface roughness is a Gaussian cyclostationary process and its statistical properties are discussed. In particular, its autocorrelation function is derived and its dependence on relevant roughness parameters is studied. Subsequently, the problem of incorporating such a roughness description into the Integral IEM model is addressed and simulation results are given in the case of one dimensional surfaces. The sensitivity of backscattering coefficients to intrinsic surface parameters and to the range of considered spatial scales is assessed.

Backscattering Simulation from Soil Surfaces

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Over the past few years, the e.m. description of backscattering from rough surfaces has been extensively investigated due to its applications in microwave remote sensing.

Rough surfaces have been traditionally described as bidimensional stationary Gaussian random processes having a fixed autocorrelation function. According to this description, statistical parameters characterizing the e.m. response of random surfaces are the heigth profile rms (s) and the correlation length (l).

In effect, the analysis of ground measurements carried out over different test sites may indicate that natural surfaces show properties of self-similarity and non stationarity. Such a behaviour may be accounted for in the framework of 1/f processes which are characterized in the spectral domain by their power density function S(f)=c/f**k. However, such processes possess self similarity over the infinite range of spatial scales whereas real surfaces may show fractal properties only in a finite range of spatial scales.

The objective of this paper is to investigate the impact of a multiscale roughness description on the surface backscattering response.

To achieve this goal, a Monte Carlo simulation based on the Kirchhoff e.m. approximation has been implemented and, as first step, validated over a wide set of classical stationary surfaces.The simplified e.m. approach requires to confine the study only to the case of moderately rough surfaces. Subsequently, self-similar surfaces have been generated by using the Successive Random Addition Algorithm (sraa). Surface sizes up to 100 wavelengths x 100 wavelengths are achieved. In this case, relevant statistical parameters are the profile heigth rms and the k exponent. The distributions of surface curvature radii and rms slope as function of surface rms and k are studied and surfaces satisfying the Kirchhoff conditions have been selected. Then, copolarized backscattering coefficients are derived by averaging a large number of independent realizations.

A sensitivity study of backscattering to roughness states, moisture values, as well as to surface area and the range of included spatial scales is performed.

On Inverting Backscattering from Bare Surfaces

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The possibility of retrieving soil moisture information over bare soils by using SAR data has been extensively investigated during the last years. However, its feasibility still remain to be quantitatively assessed. As it is well known, backscattering responses of bare soils is essentially determined by their roughness states and only to a lesser extend it depends on the soil moisture content. Previous works have demonstrated that soil roughness possesses, in natural conditions, a very large variability even within apparently homogeneous fields. Such a variability may require fundamentally different assumptions about roughness statistics with respect to traditional hypotheses which model natural roughness as a zero mean Gaussian stationary process with an associated autocorrelation function.

A better understanding of roughness variability may be achieved by considering natural roughness as a fractal random process. According to such an approach, the correlation length is a pseudo parameter because it depends on the extension of the sampled profiles over which it is estimated. A wavelet expansion of random fractals characterized by the spectral power S(f)=c/f**k has been recently proposed to model natural roughness and it is here exploited. Relevant roughness parameters in this approach are the profile rms and the k exponent.

In this paper, copolarized backscattering coefficients obtained by means of the IEM model matched with a roughness description in terms of 1/f processes are inverted to retrieve dielectric constants. The purpose of the paper is to assess the feasibility of retrieving soil moisture content over bare fields by using SAR data currently or in the near future available on a continuous basis, i.e. ERS2, JERS1, and the forthcoming ASAR on board of ENVISAT. For this reason different SAR configurations in terms of polarization, frequency and incident angle are investigated. In particular, the multiangle geometry available for ENVISAT is simulated.

In order to reduce the number of unknowns, a priori information about the surface state are assumed. In particular, due to recent observations which have related the profile rms with agricultural practices and with seasonal periods, the profile rms has been considered known from ancillary data. To attain the IEM inversion, a neural network approach is used. This is due to their property to approximate functions starting from the knowledge of input-output couples (x,f(x)). The approximation performance in a root mean square sense is evaluated by using two different architectures, the multi-layer perceptron and radial basis function networks.

An experimental assessement of the inversion algorithm is carried out by using ERS1/ERS2 data acquired over Middle Zeeland (The Netherland) and Great Driffield (United Kingdom) test sites during 1994 and 1996, respectively.Over these sites, extensively ground data are available.

Observations of Coherent Emissions from Soils

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Observations of the microwave emissions at 1.413 (L-band) and 2.65 (S-band) GHz from a silt loam soil in Davis, California exhibited an oscillatory behavior in time as the soil was being irrigated. The oscillations are attributed to interference between reflections from the air-soil interface and the wet-dry soil interface or wetting front as the latter moved down in the soil.

The magnitude of the first oscillation at L-band was 56 K and at S-band it was 40 K, with the oscillations damping out after about 3 cycles to the brightness temperature expected for the wet soil. This was a rare and unique occurrence. The emission was modeled using a coherent model and the results show qualitative and quantitative agreement with the observations. The calculations indicate that the thickness of the wetting front is about 1.5 cm. The calculations were relatively insensitive to the soil salinity but were very sensitive to the thickness of the wetting front and to the depth variations over the radiometer footprint.

Session J09
Thursday, July 16, PM 16:20-17:40
Room 450
Radar Remote Sensing of Forests

Chairs : R. H. Lang

Characterizing Tropical Vegetation Canopies Using Multi-Frequency Interferometry and Polarimetry

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SAR Interferometry has proved to be a valuable tool for topographic mapping and change detection. In the last few years, some studies have examined the possibility of using SAR Interferometry to characterize vegetation canopies, especially tree height and canopy penetration. This characterization is feasible since it has been shown by various authors that volumetric scattering introduces decorrelation between the interferometric channels, thus establishing a causal relationship between the tree geometry and the interferometric signal.

It is expected that vegetation type, and the detailed nature of the canopy gap structure play a major influence in the amount of penetration into the canopy. Previous studies have concentrated in coniferous or deciduous tree stands, where the canopy geometry allowed for large gaps. Past data analysis has also concentrated on C or X-band interferometric returns. It is the purpose of this study to present the results of an experiment conducted to characterize interferometric returns at C and L-bands for tropical vegetation canopies. During the late fall of 1996, the NASA/JPL TOPSAR system collected C and L-band interferometric, as well as P-band polarimetric, data in Cape York, Australia. Ground truth vegetation observations were also collected, and in this paper we present the results of dual frequency height and penetration measurements into various tropical vegetation types, including rain forest, mangroves, and various types of eucalyptus woodlands. The measurement of estimated tree height and height biases inferred from decorrelation data are examined, and the feasibility of using IFSAR's for tree height measurements in tropical forests is assessed.

In addition to measurements of tree height, interferometric data can be used to perform terrain classification for different tree types. We present a tree type classification scheme which uses single or multiple frequency interferometric data, as well as mixed interferometric and P-band polarimetric data, for the identification of different vegetation types. The accuracy of the classification algorithm is assessed by comparing against ground truth data collected by the Queensland Arboretum in support of the CYPLUS project. The relative advantages of classification at various frequencies and using various channel combinations is assessed. The implications of these results for performing terrain classification using data from the forthcoming NIMA/NASA Shuttle Radar Topography Mission (SRTM) is also examined.

Surface Roughness Effects on Active & Passive Microwave Remote Sensing of Forests

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A discrete scatter model has been used to examine passive and active remote sensing of soil moisture under a forest canopy in the presence of surface roughness. The forest is modeled with a distribution of lossy dielectric cylinders which represent the tree trunks, branches and needles in the forest layer. The interface between the vegetation layer and the soil is taken to be a smoothly varying surface at the L band frequencies being considered. Based on these assumptions, a Kirchhoff's approach has bee n used to model the rough surface. The bistatic scattering coefficient from the forest layer is computed by employing a Distorted Born approximation, in conjunction with the Kirchhoff model for the surface. In the active case the backscattering cross sect ion is obtained directly from the bistatic result, while in the passive case Peak's approach is used to relate the integrated bistatic scattering coefficient to the brightness temperature of the forest.

The model has been validated using measurements made on a hemlock stand in Howland, Maine during the Forest Ecosystem Dynamics Experiment (Summer, 1990). Measurements were made of tree architecture, surface moisture and roughness for the above site. Rem ote sensing observations were made at L-band by a passive sensor, the PBMR (Push Broom Microwave Radiometer) and an active radar sensor, the AIRSAR. The model predicts reasonable agreement with both sets of observations (passive and active) using the me asured canopy architecture statistics, soil moisture and surface roughness.

The calculations show the role played by surface roughness in determining the sensitivity of both passive and active sensors to soil moisture. This sensitivity will be examined for both active and passive sensors as a function of surface roughness and a ngle of incidence. In the active case radar backscatter is sensitive to the incoherent scatter from the surface as well as the coherent and incoherent scatter from the trunk-surface interaction term. For small surface roughness, the coherent trunk-surface interaction term is the dominant surface component sensitive to soil moisture. As the surface roughness increases, this term is replaced by incoherent trunk-surface scatter and the incoherent scatter from the surface. In the passive case, the sensitivity to surface roughness differs since the brightness temperature only responds to the integrated bistatic cross section of the forest.

Measurements over Forested Areas : a Microwave Attenuation and Backscatter Experiment at 2.2 and 5.8 GHZ

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Interaction phenomena in the 1-10 GHz band between an electromagnetic signal and vegetation represent an interesting physical topic for all applications related to forward propagation and backscatter problems. As a matter of fact, remote sensing applications aim to retrieve forest geophysical parameters by means of radar data and telecommunication services providers are very interested in attenuation prediction methods. ERABLE project (granted by CNET) takes place in this context, with the double objective of measuring forest backscatter coefficient and vegetation induced attenuation and comparing data with physical models predictions. Nowadays, satellite observations may add large scale measurements, nevertheless description of absorption and diffusion mechanisms takes advantage of small scale experiment, which imply measurements over well controlled area.

In the framework of the ERABLE project, two forest sites have been chosen in Fontainebleau area (60 km SE from Paris), respectively a pine stand and an oak one. The goals of ERABLE are to measure in the same conditions and with the same instruments both attenuated and backscattered signal through a forested area. To accomplish this, a measurement campaign has been performed by means of a radar operative at 2.2 and 5.8 GHz in monostatic and bistatic mode, simultaneously with ground data measurements. Incidence angles are between 50 and 70 degrees off vertical direction. Two experiments have been done, each one lasting 4 weeks, during July 96 and March 97. These periods have been chosen to observe seasonal effects, if any, and quantify leaves attenuation contribution on deciduous trees.

The first step of the project concerns attenuation forecast. Measured data have been compared with simulations results given by MIMICS and Karam & Fung microwave models, properly adapted to transmission aims. Geometry of sites and trees' architecture have been described starting from ground measurements. Oak stand attenuation values at 5.8 GHz are always greater than those measured at 2.2 GHz, during summer. Winter data are almost the same at both frequencies. As expected, leafy trees contribute to attenuation is very impressive in comparison to winter measurements. Differences up to 10 dB have been observed at 5.8 GHz measurement. Minor differences have been observed for pines trees.

Models performance strongly depends on the knowledge of site geometrical and electromagnetical parameters. Predictions results are pretty good for what concerns pine stand and satisfactory for oak one. A lack of information about branches density and orientation on oak tree suggest us the opportunity of further improvement.

Contribution to the Analysis of the Interaction of an Electromagnetic Wave with a Forest. A full Wave Approach Based on an Integral Representation

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Introduction

The analysis of the interaction of an electomagnetic wave with a forest is mainly based on a radiative transfer model [1]. The latter ignores the phase of the electromagnetic field and provides intensity information only. However, the knowledge of the phase will improve the interpretation of experimental and numerical results and it plays a key role in interferometric techniques.

Model

For this purpose, we have developped a full wave model of the interaction based on an integral representation of the fields. As a first step in our analysis, the leaves and small branches are modeled by a homogeneous layer placed over a biperiodic array of cylinders representing the trunks. The latter lies on the ground, described by a semi-infinite medium with a plane interface. The homogenized model of the canopy is suitable for the case where the wavelength of the incident wave is large compared to the leaves and branches dimensions, which will be the case here.

Making use of the Green's function of the multilayered model of the forest and of Floquet's theorem we were able to set an integral representation of the fields. The unknowns are the values of the electric field inside the trunk and they are obtained by means of a method of moment applied to the integral equation they satisfy.

Results

We consider realistic values of the permittivities and conductivities for the canopy, the trunks and the ground and we calculate the complex valued reflection coefficient R of this approximate model of the forest. The angle of incidence varies between 0° and 45°. Energy conservation is checked and the results are compared with those obtained from a 2D model [2].

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Session K07
Thursday, July 16, PM 13:40-17:40
Room J
Propagation Effects and Models

Organisers : L. Bertel, Y. Beniguel
Chairs : L. Bertel, B. Arbesser-Rastburg

H.F. Channel Modelling Including Antennas and Propagation Effects

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Introduction

A vectorial model of H.F. link is presented. It takes into account the effects of antenna polarization at both the transmitter and receiver,and the effects of ionospheric channel (polarized modes, doppler frequency, group delay, phase delay).

Scalar and vectorial H.F. model

As far as H.F. communication links are concerned, there are four important factors which define the parameters of total wave. The first factor is the splitting of the incident waves into the two magnetoionic waves, the ordinary (O) and the extraordinary (X) modes. This phenomenon depends of Budden limit conditions and polarization of the transmitting antenna. Antenna responses obtained for each mode are represented by G_{lk}, where l is the antenna type and k is the mode [1]. The second factor depends on the effects of propagation in the ionosphere. The different layers D, E, F1, F2 introduce multipath, attenuation a_k, doppler frequency fd_k, group delay τg_k, phase delay τp_k. The deterministic part of these parameters can be obtained from ionospheric prediction software such as LOCAPI [2], ASAPS, or VOACAP. The random part follows slow variations. The coherence time is reported to be greater than 10s [3] and the coherence bandwidth is on the order of 50kHz [4]. The third factor depends on how the wave exits the ionosphere where all the modes are polarized by Budden limit conditions. This is the vectorial part of model and is defined by $[I_k]$ (3x3) orientation matrix of an ellipse, and V_k (3x1) represents ratio polarization for each k mode. The last factor is the projection of N waves or modes on receive antenna base [4]. The incoming waves are projected on receive sensor of n_a antennas to obtain a signal vector s (n_ax1). Transformation is realized by the transfer matrix $[T]$ (n_ax3) of sensor (complex response) [3].
The H.F. model is represented by the following expressions :

$$\vec{h}(\tau,t) = \sum_{k}^{N} G_{lk}\, a_k\, [I_k]\, \vec{V}_k\, \delta(\tau-\tau_{gk})\, e^{-2\pi j.f_k(t-\tau_{pk})} \qquad \vec{s} = [T]\,(\vec{h}(\tau,t) * e(t))_\tau + \vec{n}$$

where $\vec{h}(\tau,t)$ (3x1) is the vectorial time-variant impulse response, $f_k = fo + fd_k$, fo is the transmitted frequency, $e(t)$ is transmitted signal ($e(t)=m(t)$ in wide band, $e(t)=1$ in CW), n is the gaussian noise vector introduced by the receiver.
The use of delta function $\delta(t)$ is justified for bandwidth of $m(t)$ smaller than 50kHz.
To illustrate, the figure 1 shows the sensor used in the measurements [5]. It is composed of two (n_a=2) cross loops (East-West and North-South directions). The figure 2 shows an example of narrowband measurments which contains two complementary modes (O and X) (fo=6.175MHz, 11/03/96). The opposed polarization of O and X shown figure 3.

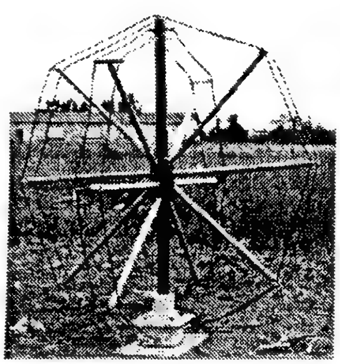

Fig : 1

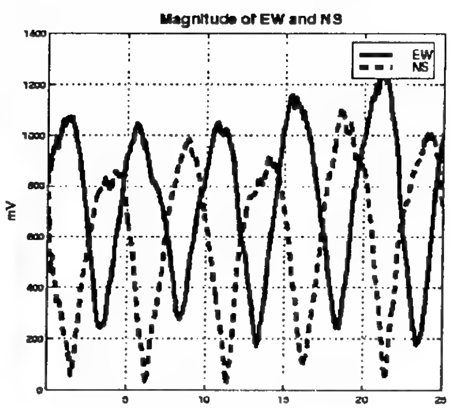

Fig : 2

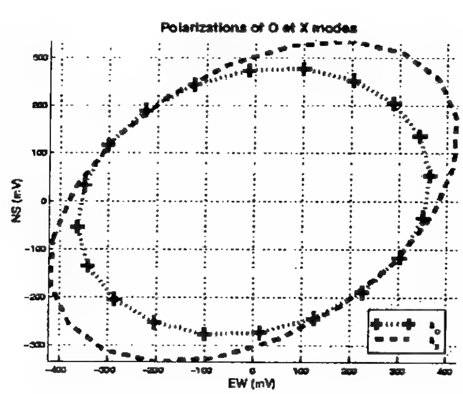

Fig : 3

Conclusion

The suggested model describes completely a H.F. link using scalar and vectorial representation. The use of vectorial sensor (several antennas) permits the estimation of polarization of each modes. The signal vector s can be used to improve results of radio direction finding (narrow band) or to reduce effects multipath in digital communications (wide band < 50kHz).

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Pratical Methodology for Estimation of HF Channel Response

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In most modern modems which are employed in HF communication, channel impulse response estimation constitues a first step of various tasks including scattering function computation and channel equalization.

In this paper, we propose a methodology to estimate the time varying fading multipath HF channel response numerically utilizing the data from controlled experiments in which the transmitted waveform and the received signals form the ionosphere are recorded and coherently processed. Due to the slowly time varying nature of the ionosphere in midlatitudes, we concentrate on the pulse-to-pulse variability of the channel impulse response whose state space equation for the pth pulse can be given as

$$h_{p+1} = h_p + u_p \tag{1}$$
$$r_p = A_p h_p + v_p \tag{2}$$

where h_p is the channel impulse response at baseband ; u_p is the variation on the channel impulse response ; r_p is the received signal at baseband; A_p is the matrix due to the transmitted signals and v_p is the variation due to noise.

In this formulation, h_p's can be estimated using a standard Kalman Filter which constitutes a reliable off-line estimating scheme for time varying channel impulse response. An initial condition estimation can be based on least squares optimization. For testing of the method, we will generate the channel output using Watterson channel model for good, moderate and bad conditions as indicated in ITU-R recommendations. We will also compare the performance of the proposed estimation scheme to other approaches such as adaptive system identification algorithms.

We emphasize that the proposed method can be extended for the estimation of channel impulse response parameters rather than estimation of channel impulse response itself.

First Experimental Approach to the VHF Channel Characterisation Collocated Antenna Diversity in Forest Environment

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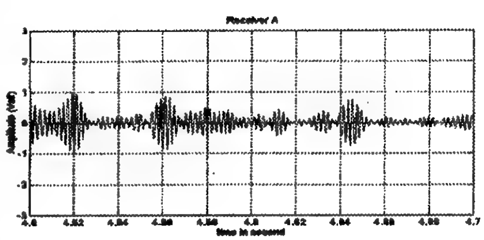
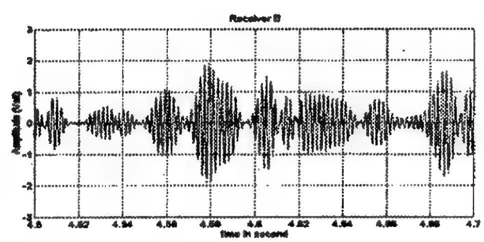
This paper deals with antenna effects on the characterization of the VHF channel in a forest which is strongly affected by multi-path propagation. Experimental results are presented which give Doppler frequency shift, path delays and antenna effects.

The transmitted signal is represented by $e(t) = e^{j((f_l + f_c)2\pi t + \varphi)}$ where the carrier is f_c = 64.2 MHz and f_l = 500 Hz. The receive equipment consist of two collocated crossed loop antennas which are placed on the roof of a van. Each receive antenna is connected to a receiver '(A, B).
The demodulated signals at the output of the receivers are shown in figures 1 and 2 when the van was traveling at 40 km/h. The differences between both show the effect of the antenna diversity over the 0.2 sec observation interval.





The low-pass signals at the receiver's output can be represented by $r_i(t) = \sum_n \alpha_n(t).F_{in} e^{j2\pi(f_l + f_{d_n}(t)).(t - \tau_n(t))}$.

The complex F_{in} represents the i^{th} antenna effects, $\alpha_n(t)$ is the space attenuation, $\tau_n(t)$ is the propagation delay for the n^{th} path [1] and $f_{dn}(t)$ is the Doppler caused by the movement of the van. From figures 1 and 2 the propagation and antenna effects can be observed. For example at t = 4.52 sec, one is zero while the other is not.

The experimental results show that the antenna response has to taken into account in channel modeling. In addition to the narrow-band technique described above, wide-band techniques similar to those used by D. Cox [2] are currently under investigation. This will provide the multi-path channel characteristics. The use of the polarization diversity antenna will be include to improve transmission in the VHF range.

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VLF/LF channel characterization

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Channel characterization could be described by 2 different ways : first signal propagation and secondly noise which is our interest subject in this paper.

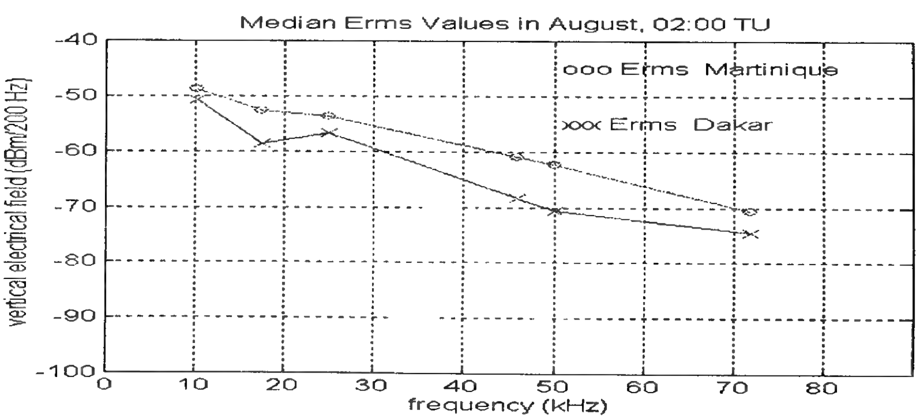
VLF/LF propagation is supposed known, several simulation programs are available [1], [2].

On the other hand, radio noise, of which most of the natural VLF/LF noise observed everywhere in the world is lightning-generated, constitues a limitation to radio reception.

CCIR data [3] represent the atmospheric noise reference. But the report 322 is characterized by several lacks : only 2 frequencies are studied in this band, the data are over three decades old, and are not sharp enough (data are given in a four hours time block and season).

That the reason why a new measurement bench is constructing in several places throughout the world in order to characterize electromagnetic noise in the 10 - 90 kHz (VLF/LF) frequency band. This specific receiving system posseses a very high dynamic (120 dB). Our goal of this measurement program is to improve communication in the VLF/LF band by providing more up-to-date and complete informations about the properties of the VLF/LF noise. We intend to have a better noise temporal, frequential and spatial understanding.

We present some of the first noise statistics that can be derived from the measurements such as average and rms noise amplitude variation (an example is shown), noise impulsiveness parameter Vd (ratio between Erms and Eavg) and amplitude probability distribution.



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Mobile Radio Channel Characterisation with UMIST Chirp Sounder

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The advantages of chirp sounders have long been recognized and hence they are widely used in HF measurements. However, their application to mobile radio channels has been limited due to the wideband requirements and the fast repetition rates. Recently, chirp sounders which use digital techniques for the generation and the compression of chirp pulses have been reported. These sounders have architectures which store the digital samples of the chirp pulse in a random access memory (RAM). Due to the high bandwidths required for mobile radio sounding, chirp sounders which use the RAM implementation generate chirp pulses with durations limited to a few microseconds. This in turn limits the processing gain of the sounder and results in oversampling of the impulse response of the channel.

To avoid the RAM limitations the sounder developed at UMIST employs a direct digital frequency synthesiser (DDFS) for the generation and the compression of the chirp signal. The sounder uses field programmable gate array logic and a microcontroller to programme the DDFS which enables the generation of chirp signals with different bandwidths and different durations. The sounder has the capability of generating chirp bandwidths up to 90 MHz, hence it is suitable for both indoor and outdoor measurements. By employing a delayed chirp replica at the receiver to mix with the incoming chirp signal, the output of the receiver is compressed in bandwidth. The output of the mixer is subsequently lowpass filtered, digitised by a low speed analogue to digital converter, stored in a RAM and logged to a laptop. Subsequently, the data are processed offline with different time and frequency resolutions to obtain the different channel descriptors which include power delay profiles, and various cumulative distributions.

In this paper, the various requirements of realizing a chirp sounder will be highlighted. This is followed by presenting the architecture of the UMIST chirp sounder. Average power delay profiles obtained from both indoor and outdoor measurements which show the resolution capability of the sounder will be presented. The advantage of using heterodyne chirp sounders will be demonstrated by presenting average power delay profiles as a function of frequency obtained from 90 MHz bandwidths soundings in Manchester city centre.

Possible Applications of HF Colocated Antennas

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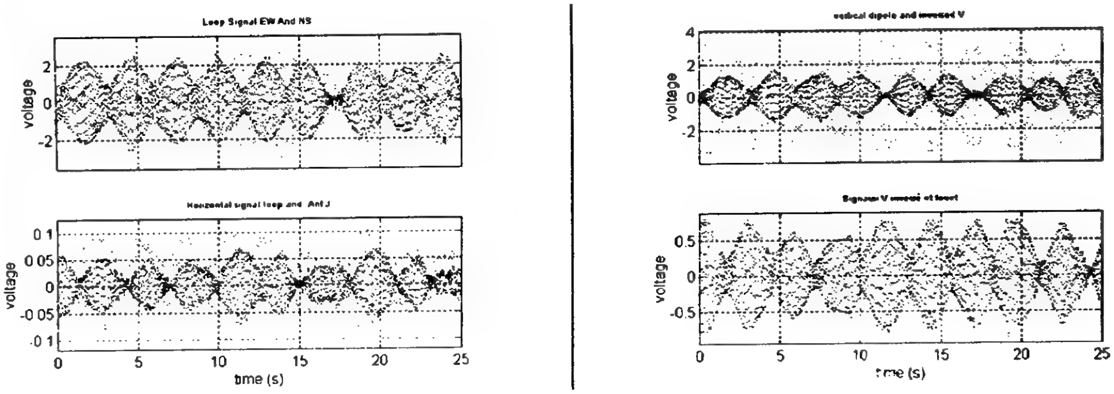
A vector signal model employed for a receiving antenna is written as : S = [H] * [E], where [H] is a [1,3] complex coefficients matrix characteristic of a given antenna and [E] is the incident electric field. With a receiving antenna denoted i, the narrow band signal s is expressed as [1]:

$$s_i(t) = \sum_k A_k F_{ik} m(t - \tau_{gk}) e^{j\omega_k (t - \tau_{pk})} + n(t)$$

where F_{ik} is the complex characteristic function (amplitude, phase) of the antenna i deduced from the [H] matrix [2] and k is the number of propagation paths.
On the next figures, experimental acquired signals on several HF colocated antennas are shown; the transmitter is a Germany HF broadcast. The receiving site is located in Brittany near Rennes (France). We can observe that fadings on the different types of antennas of the colocated sensor do not occur at the same time, and that the signals are decorrelated.



For an antenna denoted i, the F_{ik} functions are amplitude and phase dependant on the wave direction of arrival; this effect is essential in the colocated HF antenna applications.

Using the MUSIC algorithm, we can determine the direction of arrival of waves. The pseudo-spectrum is obtained from steering vector, for the colocated antennas, it has this form : a= $(F1,..,F_i,.., F_n)$ where Fi is the complex characteristic function that steering vector has not to take the space diversity into account [3].
An advantage of that method in HF direction finding, is that the large aperture receiving arrays can be reduced by a ponctual array.

Another application is the use with vectorial modems in digital communications, where multipaths effects could be reduced. Antenna or polarization diversity can be used instead of space diversity in numerous HF applications like direction finding or transmission.

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Characterization of Ionospheric Scintillation Errors A Comparison Between Different Models

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Inhomogeneities inside the ionosphere develop under the influence of instability processes. Their characteristics depend on various geophysical parameters and they may vary in a significant range as concerns their size and the strength of electronic density fluctuations.

Modelling the development of the inhomogeneities is the object of many research studies. Due to the sizes and time dependency involved, related to the mechanism under consideration, this can usually be done only in a restricted area.

For this reason including the inhomogeneities in a ionospheric medium description such as to be able to predict their influence on the characteristics of the transmitted signals is usually done in a statistical way [1]. Fluctuations data include their size, location, electronic density fluctuations spectrum, drift velocity ... These data may be obtained from measurements.

A comparison between different approaches to include the influence of the inhomogeneities in a propagation model will be presented. This will concern in particular the way to include the data and the signal characteristics resulting. Comparisons of results will include maps of phase variance fluctuations, scintillation ratio S4 and occurence statistics. These comparisons will be performed varying the carrier frequency and the geophysical parameters, namely the solar spot number and the magnetic activity index.

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High Time Domain Resolution Channel Sounder Operating in the 60 GHz Band

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The 60 GHz band seems a good candidate for future WLAN : the available bandwidth can support very high data rates, and the severe atmospheric attenuation (15 dB/km) greatly improved the frequency reuse between buildings. Then, accurate measurements of the propagation channel are needed to efficiently develop and simulate high speed digital communication systems, included new modulations schemes, coded and multiple-access techniques.

This paper describes a propagation measurement set-up dedicated to the 60 GHz band indoor channel. The wide band characterization is based on the Cox time domain method : a maximum-length pseudo random (PN) sequence is generated and BPSK modulated at 60 GHz. The received signal is down converted and the result in-phase (I) and quadrature (Q) signals are mixed with an identical but slower PN sequence. The final I and Q low frequency signals, which determines the complex impulse response of the channel scaled by a factor k, are continuously sampled and stored on a PC hard disk. The k factor is determined by the transmitter (D_{tx}) and receiver (D_{rx}) sequences data rate : $k = D_{tx} / (D_{tx} - D_{rx})$. The coherence between the transmitter and the receiver is preserved by a 20 meters cable carrying the reference crystal oscillator signal.

The PN sequence data rate D_{tx} is 400 Mbit/s, which enables to achieve a very high time domain resolution (2.5 ns) between different paths. Since the sequence length is 511 bits, delay spread up to 1.28 µs can be observed, which is supposed to be sufficient to inside buildings environment. The transmitter power is 1 dBm and the applied antennas are two identical horns. A near omnidirectional antenna is also available.

Moreover, particular cases have been taken to optimize the storage capacity and improve the maximum Doppler frequency , i.e. to avoid under sampling of the non-stationary channel. For fast varying channel, the k factor can be reduced as low as 1000, and the observation interval to only 30 ns, resulting to a maximum Doppler frequency of 17 kHz. In situation where severe attenuation are encountered, the noise bandwidth can be reduced to 4 kHz by increasing the k factor to 100.000. In any case, the sampling rate is automatically adjusted to maintain only 2 samples per channel (I and Q) each time the drift between the PN sequences is increased by one chip length. Since the data are directly stored on a PC hard disk, continuous measurements of 10 min to 18 hrs, depending on k factor, can be achieved.
First measurement results, obtained inside the laboratory, and data analysis are presented. These results will be used to develop a channel model using a simulation software (i.e. PTOLEMY). These simulations then serve as a design tool for high performance radiocommunication system in the 60 GHz band.

Performances of Two Coherent Spread Spectrum DS/FH RAKE Receivers for the Troposcatter Channel

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The scattering phenomenon in the high layers of the troposphere offers the possibility of obstructed-line-of-sight communications. The transmitted signal is scattered by the inhomogenities of the air refractivity index within the common volume of the transmitting and the receiving antenna beams. The troposcatter impulse response is a continuum multipath, with a power shape in Gamma function. Each path is statistically depicted by a Rayleigh envelope and a uniformly distributed phase in $[-\pi, \pi[$, and WSSUS channel model is assumed.

Our research work is concerned with military tactical transmissions of range limited to 200 km for transportable systems. The antenna diameters are fixed to 2,5 m. The transmission frequency is set to 5 GHz, and the available bandwidth W is limited to 40 MHz that can be separated into several smaller sub-bandwidths. This paper first presents the channel characteristics of our link and then the spread spectrum system structures we have designed. Finally simulated performances of these systems are described in detail.

The behavior of the channel directly depends on the radio link characteristics (diameter of antennas, scatter angle, distance, frequency, climate, geographical relief...). The study of our radio link configuration has led to a coherence bandwidth varying from 400 kHz to 4 MHz for a period greater than 99 % of time. Measurement campaigns have shown that the coherence time vary from 0.1 to 10 seconds.

To fight multipath propagation drawbacks, an implicit diversity technique is applied, which is obtained by transmitting a signal whose bandwidth W is larger than the coherence bandwidth B_c of the channel. Direct sequence (DS) spread spectrum techniques, while spreading the signal's bandwidth to a larger scale than the one required by the symbol rate, enable to reach this goal. The diversity order obtained is about W/B_c. In a multipath environment, the optimal adaptive receiver for broadband signal processing is the RAKE spread spectrum receiver, which performs a maximal ratio combination of the energy of the paths. It requires, however, an operation of channel estimation. The transmitted signal must then contain a known bit pattern, reproduced at the receiver, which enables to compute an estimation of the impulse response of the channel. The coherent systems we have designed using COSSAP are hybrid DS/FH spread spectrum QPSK modems for low data rate transmissions (64 to 512 kbits/s). The data stream is sliced in frames of 10 ms. Each frame of several hundreds QPSK symbols, is transmitted at a certain frequency of the FH system. In the middle of the frames, a reference sequence made of the repetition of the same m-sequence is introduced. The channel estimation is realized by a digital matched filter to this particular m-sequence. The DS bandwidth should be chosen as large as possible to increase the diversity order. But a compromise between demodulator complexity and performances has to be found.

The results, in term of bit error rate, offer a comparison of performances between several configurations of the reception scheme : real and ideal estimation, influence of the variations of the coherence bandwidth, reduction of taps number, structure of the reference sequence. For simplification purposes, carrier and data are considered synchronized, and there is no inter-symbol-interference. Finally, two architectures of complete coherent RAKE receivers are compared in term of performances and complexity. The first architecture is based on a sliding correlator and the second is based on a matched filter.

Measurement of Radiated Power at VLF/LF

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The US Navy uses large high power shore based VLF and LF transmitting systems for long range communications to platforms at sea. These transmitting antennas are some of the biggest and most powerful in the world. It is important to have accurate knowledge of the power radiated by these antennas to estimate the available coverage. In part, due to the large wavelengths at VLF/LF (6-20 km), there is no direct way to measure the radiated power and radiation resistance. Instead, these parameters are best determined indirectly by conducting an extensive field strength survey at sites located a moderate distance from the antenna, while at the same time recording antenna current. This is the time honored technique, used since the beginning of radio. The measurement technique now used is conceptually the same but with the advent of modern technology, much has changed. The equipment available now is more automated, calibration is easier and much more accurate and measuring the distance to each site is now facilitated by GPSS. A complete description of the modern version of this technique is given, including the theoretical basis and a discussion of techniques we have developed to make the process easier and more accurate. A description of the Navy's Helmholtz coil calibration facility is given, along with a discussion the method developed to provide highly accurate calibration for magnetic field measurements (better than 0.01 dB) throughout the VLF/LF band. Example data from several field strength surveys will be presented.

Session L08
Thursday, July 16, PM 13:40-17:20
Room R01
Frontiers of Electromagnetics Research

Organiser : U. Unrau
Chairs : U. Unrau, B. Lehnert

Failure of Maxwell Electrodynamics

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Maxwell's electrodynamics is based upon

1 1) the Biot-Savart law
2) Coulomb's law
3) Faraday's law of electromagnetic induction
4) the conservation of charge

The Biot-Savart law for the force between current elements violates Newton's third law and thus the conservation of energy. It only agrees with empirically correct original Ampere force law, which obeys Newton's third law, for the force on a current element produced by an entire mechanically rigid closed current loop. The Maxwell theory, thus, fails when mechanically rigid closed current loop sources for the **B** (or **A**) field are not involved. The Maxwell theory cannot, thus, be a fundamental electrodynamic theory; because it cannot give the force acting between two moving point charges.

The Maxwell theory, lacking the empirical Ampere force of repulsion between collinear current elements, cannot predict the force on Ampere's bridge, the force rupturing current carrying wires, the force driving the Hering pump, nor the force driving the Hering-Graneau submarine.

The Maxwell theory, not conserving energy, cannot account for the non-radiating Bohr H-atom.

The Maxwell theory does not predict the observed zero self torque on the Pappas-Vaughan Z-shaped antenna, where no closed current loops are involved.

Maxwell electrodynamics has only a very limited range of applicability; it cannot give, in general, the answers needed in electrodynamics. For slowly varying effects, where the rate of separation between two charges is less than $\sqrt{c}$ and radiation is not involved, Weber electrodynamics is an ideal fundamental theory. It is based upon the potential energy

$$U = (qq'/R)\,[1-(dR/dt)^2/2c^2].$$

For slowly varying effects, in contrast to the many failures of the Maxwell theory, the Weber theory is empirically correct. It yields the empirically correct original Ampere force law, as well as the Faraday law of electromagnetic induction.

For rapidly varying effects, where relative velocities are limited to 2c, and where radiation is also included, the Weber-Wesley field theory is the best electrodynamic theory to date. Four potential fields are involved, the usual ϕ and **A** fields plus two additional Γ and **G** fields. the Weber and Maxwell Theories are special limiting case of this more general electrodynamic.

The Impact of Topology and Group Theory on Future Progress in Electromagnetics Research

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There are a number of phenomena which give validity to the notion that the *A* potentials are not merely mathematical conveniences, but have physically measurable effects - but only in certain well-defined interferometric situations. These well-known phenomena are examined in Refs§. The conditions for the *A* fields to have physically measurable effects are not associated with the usual force fields whose transformation rules are described by group U[1] symmetry form. The conventional "Maxwell theory" applies to these "infinitely"-connected situations. The conditions required for measurable *A* field effects are fields of group symmetry SU[2] and above. The topology required for the *A* field to be physically measurable is that of two-to-one, or many-to-one mappings. In those situations electromagnetism is then more fully understood as a gauge field with an "internal space" that is other than infinitely connected.

Quite apart from the use of the *A* field in practical engineering devices, e.g., the ring laser gyro (Sagnac effect), digital switches (Aharonov-Bohm effect), Berry's Phase, toroidal antennas, etc., this new way of regarding the electromagnetic field may have impact on unified field theory in that attempts to unify other force or gauge fields with conventional U(1) electromagnetic force fields may be misguided. Unification of other force or gauge fields with SU(2) or higher order electromagnetic gauge fields may be required.

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An Extended Electromagnetic Theory

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An extended Lorentz invariant form of Maxwell's equations is based on a nonzero divergence of the electric field *in vacuo*. Such a concept does not have to be less conceivable than the nonzero curl of the magnetic field in a conventional electromagnetic wave. In addition to the displacement current this form includes a "space-charge current", acting as an extra source of the electromagnetic field. Thereby new features are predicted to exist, such as steady (time-independent) electromagnetic equilibria and additional types of dynamic (time-dependent) states including new wave modes. Whenever being necessary, relevant quantum conditions are further to be imposed.

Among the equilibria, there are axisymmetric "particle-shaped" states where the configuration is bounded in the radial and axial directions, and "string-shaped" states which are uniform in the axial direction. The general solution of both these states can be given in terms of a generating function. Integrated field quantities are then obtained which represent a net electric charge, magnetic moment, mass, and angular momentum (spin). The former states can reproduce most of so far known data of the electron and muon which have a nonzero net electric charge and an extremely small radial dimension, as well as of the neutrino which has a vanishing net electric charge and a very small mass. The latter states have no net electric charge and no magnetic poles, and they could apply to the string model of the hadron structure.

Among the new wave types, there are plane and axisymmetric modes. Plane non-transverse electromagnetic space-charge waves can satisfy the otherwise problematic boundary conditions for total reflection at the interface between a dissipative medium and *vacuo*. The axisymmetric propagating wave modes and packets have a general solution which also can be derived from a generating function. They carry an angular momentum, such as that of the photon in the capacity of a boson, have no net electric charge, and possibly include a net magnetic moment and an axial magnetic field component in the direction of propagation. This component may become small and difficult to detect. The obtained result is in any case reconcilable but not identical with the ideas of Evans and Vigier and of Roy and collaborators about a very small but nonzero rest mass and an axial magnetic field component of the photon.

In the cases of axisymmetric "particle-shaped" states and of axisymmetric wave modes the present approach avoids the divergence which otherwise arises in conventional theory for the field quantities, either at the axis of symmetry or at large distances from the same axis.

An Explicit Example of a Family of Non-Planar Free-Space Electromagnetic Waves Containing Magnetic Scalar Potentials

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Electromagnetic waves (EMW) are formed by electric and magnetic fields, together solution of Maxwell's equations. The magnetic field is solenoidal always, while the electric field is solenoidal in charge-neutral regions only. In the conventional interpretation, free-space electromagnetic fields are transverse to the direction of propagation and there exist a electric scalar potential but not a magnetic companion.

We use a simple explicit example to build step-by-step the case for magnetic scalar potentials :

1) Start with a linearly polarized plane EMW in free-space and obtain the directional and energy transport properties.

2) Introduce a variation consisting of a magnetic field component along the direction of a propagation of the EMW. This EMW is now a linearly polarized non-planar EMW, that leads to propagation of energy on the whole y-z plane in contrast to the plane case where energy only propagates along the z-axis. Two different families of energy propagation on the y-z plane are identified :

- ***a)*** When the wave numbers of the longitudinal and transverse magnetic components are commensurable, then the longitudinal transport of energy is the same as in the plane EMW, but there is now a novel lateral transfer of energy,
- ***b)*** When the same wave numbers are incommensurable, the non-planar EMW is non-periodic, and the transport of energy along the direction of propagation is smaller than in the plane case. Such energy is dissipated sideways.

3) Introduce a vacuum with a magnetic scalar potential, and identify the existence of currents, even in charge-neutral regions.

Finally, to connect these EMWs to our new non-periodic solutions of the homgeneous wave equation [*Found. Phys. Lett.* **10**, No. 1(1997)31-41], the EMWs and the main physical properties are expressed in spherical coordinates.

Relation between Weber's Eectrodynamics and Maxwell's Equations

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Weber's electrodynamics is based on a force law which depends on the distance, relative velocity and relative acceleration between interacting charges. It is completely relational, follows the principle of conservation of energy, linear and angular momentum, and has the same value in all frames of reference. From it we can derive the set of Maxwell's equations with some restrictions, as discussed in our book Weber's Electrodynamics (Kluwer Academic Publishers, Dordrecht, 1994). In this work we analyse what needs to be modified in Maxwell's equations if we accept Weber's electrodynamics, and the experiments giving support to this new view. These are related with the motional electric field (related to Gauss's law), to the longitudinal forces in open mechanical circuits (related to Ampere's circuital law) and to unipolar induction (related to Faraday's law). The experiments discussed involve the electric field outside stationary wires carrying dc currents, the exploding wire phenomena, the electromagnetic impulse pendulum (A. K. T. Assis and M. A. Bueno, IEEE Trans. Magnetics 32, 431-436 (1996), Equivalence of Ampere and Grassmann's forces), and those of unipolar induction. We discuss the controversy Ampere versus Grassmann-Biot-Savart, the origin of the self-inductance of circuits (A. K. T. Assis, Eur. J. Phys. 18, 241-246 (1997), Circuit theory in Weber's electrodynamics) and the propagation of electromagnetic signals in conducting media according to Weber's electrodynamics. A comparison is made with Lorentz's force or Lienard-Wiechert potentials.

Motional Induction Without a Magnetic Field

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The force of induction on a charge q in a magnetic vector potential field **A** is given by:

$$F = -qdA/dtc = -q\,\partial A/\partial tc - q(V\cdot\nabla)A/c \qquad (1)$$

In Gaussian units, where V is the relative velocity between the charge q with velocity v and the rigid source of the A field with velocity v', or V=v-v'. Motional induction occurs when $\partial A/\partial t = 0$. Because the Maxwell-Lorentz theory, apart from the Coulomb force, prescribes a force only when a magnetic filed $B = \nabla xA$ exists; the case of motional induction with a vanishing B field is generally overlooked or even denied. But induction without a B field is not at all unusual, such as the induction produced in the outer secondary winding of a toroidal transformer.

The magnetic vector potential A field is not zero outside a long thin solenoid, even though the magnetic B field itself is zero, $B = \nabla xA = 0$. From Eq (1) above the force on the electron of charge e and velocity v moving by the solenoid in the Aharonov-Bohm experiment is not zero. The force is given by

$$-e(v\cdot\nabla)a/c$$

It may be readily shown that this force accounts for the observed phase difference between electrons passing on the two sides of the solenoid.

An emf is induced in a long straight wire in the Hooper-Monstein experiment when two magnets of opposite polarity are moved symmetrically toward (or away) from the wire with the speed ' sot that $B = \nabla xA = 0$.

In the Maronov motor a circular ring motor is passed around a toroidal magnet, such that the vector magnetic potential A varies around the ring. when current flows in the ring, the longitudinal force dF_ϕ on the current electrons in the ring, qv = ids, is determined, according to Eq. (1) above, by the longitudinal variation in the A field along the ring, thus

$$dF_\phi = -ids\delta A/\delta sc = -idA_\phi/c \qquad (2)$$

When the current is fed in and out at the appropriate locations the net tangential force on the rotor, as given by Eq. (2), causes the rotor to rotate.

Local Instantaneous Energy and Momentum Densities of the Free Electromagnetic Field

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It is known, that the energy and momentum densities of the classical electromagnetic (EM) field are defined ambiguously [1], [2]. Namely, the Poynting vector is defined to a certain vector whose divergence is zero (divergence freedom). That is the reason of common opinion, that the instantaneous and local momentum density has no physical meaning. However, the recent investigations of pulse propagation through photonic band-gap structures stimulate the consideration of the local values of EM field momentum [3].

The divergence freedom cannot be eliminated within the framework of Maxwell equations only, and we invoke the external ideas for the construction of the quadratic forms in electrodynamics. According to the principles of continuum mechanics, we introduce the partial components of wave motion, which are circularly polarized waves. The quadratic forms for N-wave packet field (energy, momentun and momentum flow densities, etc) consist of N proper and $1/2(N^2-N)$ interference contributions. Since the proper contributions can be obtained from interference ones, the problem is reduced to the consideration of pair interference contributions.

The novel expressions for interference energy and momentum densities have been proposed. The new expressions for the electric and magnetic energy densities contain the time derivations according the concepts of the dynamical systems description. The relation between instantaneous momentum density and the Poynting vector **ExH** has been derived. The relativistic generalization of the derived scalar and vector balance relations for vacuum is made. The new 4-tensor of momentum-energy of free EM field is constructed. This tensor is symmetric, its trace is zero for proper contributions and is nonzero for interference ones, which is essentially different from traditional results. The formalism proposed allows us to introduce not only 4-tensor of the momentum energy, but 4-vector of momentum-energy as well.

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Electrodynamics in an Electric Cusp and Uncharged Particle Acceleration by Electric Reconnection

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Electric cusp is an electrically neutral point across which electric field reversal occurs and is a bifurcation point as well as a saddle point in terms of electric potential and/or electric field. Electric reconnection is a phenomenon in which electric field lines in one direction tend to connect to other adjacent field lines in the opposite direction and by which energy stored in electric fields is released rapidly to be transferred to other kind of energy such as kinetic energy of particles, depending on the environment. Electric cusp and reconnection is analogous to magnetic cusp and reconnection familiar to plasma physicists as well as geo-astro physicists, and offers a basic concept and a variety of applications, not only to electrohydrodynamics in fluids but also to electrodynamics in a vacuum. Surprisingly, however, an electric version of field-line merging-reconnection has never been discussed except my preliminary reports (for instance, [1]).

First of all, electric potential and field perturbed by a spherical conducting particle placed in an idealized electric cusp with a quadrupole configuration are evaluated. Then a general prescription to particle dynamics in such a cusp is given on the basis of both Newtonian and Hamiltonian descriptions, introducing a new electric force arising from induced charges in the form of a tiny quadrupole.

Particle trajectory, velocity, and acceleration are obtained analytically near a cusp region. It is found that a new type of particle acceleration may occur in an electric cusp, even though the particle is uncharged, as a result of an energy release or partial conversion of electrostatic energy to kinetic energy of the particle. In particular, when a particle is located in a mirror plane, the equation of its motion is solved exactly but numerically with particular reference to upward motion of a dust particle above the ground for horizontal electrification of thunderclouds.

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ιιoton Tunneling Experiments and some Aspects of their Interpretation

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Several recent experiments have revealed that electromagnetic wave propagation velocities are possible which exceed that of light in vacuum: so-called superluminal velocities. It is important to note that these superluminal velocities concern propagation characteristics which are regarded to be representative for signal and information exchange, e.g. movement of the peak amplitude of a wave packet or of its center of gravity.

First, these experiments and their technological challenges shall be described: microwave propagation measurements in undersized waveguides and through bandstop-filter configurations as well as optical transmission experiments with bandstop-filters; both have been performed in the frequency and in the time domain. The similarities and differences are discussed as well as their common result of superluminal velocities. Meanwhile this result is out of doubt since it has been reproduced in several laboratories and with all the different experimental setups.

However, the discussion on the interpretation has still not ended. In the framework of classical electromagnetism there is nothing more to say about propagation velocities that only the so-called front velocity is defined in a unique way: by the time points when a field amplitude changes from exactly zero to non-zero values. The value of that velocity is c, the vacuum velocity of light, also for the tunneling case. However, this definition has no practical meaning, since it can only be defined and not measured. Every detector has a threshold limit for detection thus a certain energy must be present which as a minimum is that of a single photon. Defining propagation characteristics for these real cases, problems begin to emerge resulting e.g. in superluminal transmission velocities. At least the question arises whether the tunneling experiments give evidence for superluminal tunneling propagation of single photons.

Fractional Paradigm in Electromagnetism

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In recent years we have been interested in developing the bridge between the concept of fractional calculus and electromagnetic theory [see e.g., the review article 1]. Fractional calculus is an area of mathematics that addresses the operations of differentiation and integration to arbitrary non-integer real or complex orders [2]. We have shown that by bringing these fascinating mathematical tools into electromagnetic theory certain interesting features can be explored and addressed [1, 3-5]. We then generalized this idea to fractionalization of some other well-known operators in electromagnetism [3-5]. For example, we have shown that the cross-product and curl operators, which are extensively used in electromagnetic theory, can be fractionalized and such fractionalization can lead to fractionalization of the concept of duality in electromagnetism [3-5].

Our previous work has now led us to introduce the concept of fractional or intermediate paradigm in electromagnetic theory. In the mathematical treatment of electromagnetic theory, for a given general problem we often solve canonical cases. If, for example, we just consider two canonical cases as "Case 1" and "Case 2", we can symbolically show the chart of Fig. 1 where the box entitled "problem" is what describes any general problem of interest, and the two boxes "Case 1" and "Case 2" indicate the two canonical situations for the chosen problem. One may then ask the following questions: Are there any "intermediate" situations between the two cases represented as canonical situations for the "problem"? In other words, as symbolically depicted in Fig. 2 can we have fractional "intermediate" paradigm between the two cases shown in Fig. 1? Such fractional paradigms may lead to novel problems in electromagnetic theory with potential applications.

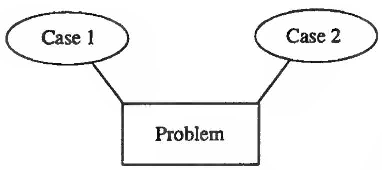

Fig.1

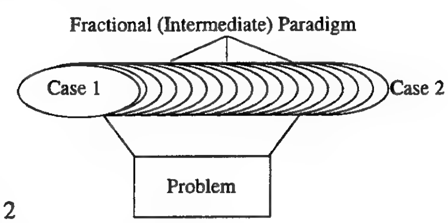

Fig. 2

In this talk some of our latest results regarding mathematical and physical aspects of fractional paradigm in electromagnetic theory will be presented and their salient features will be mentioned.

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Session M07
Thursday, July 16, PM 13:40-17:20
Room R03
Material Measurements II
Workshop on Complex Media and Measurement Techniques
Organiser : Ph. Gelin
Chairs : Ph. Gelin, M. Merceur

Measurement of Microwave Characteristics of Materials a Working Group for Standardization

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In various fields such as medical applications, microwave circuits, stealth technology, communications, meteorology or radioastronomy, new materials have been developed often based on new technologies. With regard to performance, their microwave characteristics (dielectric permittivity and magnetic permeability) must perfectly be optimized, measured and controlled.

In order to define an accurate and reliable characterization method, several industrial firms, universities and public research laboratories, have formed a working group in order to compare their different methods and facilities.

One of the aim of this groupe created in 1992, was to define a method for strandardization purposes. Several methods (waveguides, cavities, free space, ...), were tested with different dielectric and magnetic materials. The rather high dispersions observed during the first comparative campaign have now been reduced considerably.

The method developed by the A.E.C. (Atomic Energy Commission), particularly convenient for the characterization of homogeneous isotropic material, was chosen for standardization.

The cell is a coaxial circular line enabling broadband measurements of cm^3 -size samples. The machined sample is conditioned in a special sample-holder so as to eliminate air gaps. An electrically conductive cold brazing maintains the sample in the right position without affecting the material properties. The method has been qualified and its accuracy determined depending on the nature of the measured parameter and its numerical value. In all cases uncertainty is less than 3%.

This method can be extended to other types of materials and to measurements under various environmental conditions (temperature, magnetic field, mechanic stress).

The results of the working groupe, as well as the method chosen for standardization, are presented.

Reference

Dixièmes Journées Nationales Microondes - SAINT MALO - 21-22-23 mai 1997 : « Normalisation des méthodes de mesure micro-ondes des matériaux - Bilan des actions menées depuis 1992 » Groupe normalisation des mesures micro-ondes des matériaux absorbants.

Improvement of Measurement Performance of an Open-Ended Waveguide Characterization Method

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Thanks to the increase of today's computer performance, the characterization methods which required a long computer treatment to solve the inverse problem ($\varepsilon,\mu = f(S_{ij})$) become interesting and offer new possibilities of charaterization with better accuracy.

The circular waveguide radiating into a layered medium has many good points, such as the simultaneous characterization of complex permittivity and permeability, and the dieletric parameter and the thickness of materials with metal backing. The operating modes are the TE_{11} or the TE_{01} modes.

The modelling of a multilayered medium is necessary to take into account the short-circuit as second medium for example but also to take an air gap into account between the flanged waveguide and the sample, for a non contact charaterization. This air gap permits to minimize the air gap problems of flanged waveguides. With a change in one of the known media (thickness or permittivity), few measurements of the reflection coefficient of the sensor allow the simultaneous characterization of ε and μ or avoid the multiple solution problem.

The insertion of an adapter layer isolating the flanged waveguide allows the characterization of liquid medium and improves the accuracy of the method.

The introduction of a thick iris in the flange allows a reduction of the tested surface. The same iris filled with a dielectric material with low losses permits the isolation of the waveguide for the liquid characterization and improves the precision on the determination of ε.

Finally, the use of several sizes of waveguides permits a broadband characterization from 3 to 110 GHz and some measurements of dielectric materials have been realized for temperature higher than 1000°C at 10 GHz.

Electromagnetic Charactérisations of High Temperature Superconductors : State of the Art in France

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High temperature superconductors (H.T.S) have been discovered about 10 years ago. Applications working at liquid nitrogen temperature (77K) have been already demonstrated in different Laboratories. Some commercial devices are now available on the market either for large scale applications (i-e. high current) or small scale applications (i-e. low current). In this latter case applications concern mostly mobile communications (in microwaves) and medical imaging (in RF). For the applications, the superconducting materials used are in the form of film (generally $YBa_2Cu_3O_7$) deposited on a dielectric substrate (MgO, $LaAlO_3$, sapphire...). Prior to the development of applications, it is necessary to characterize the materials with physical, chemical, electrical methods....

To the best of our knowledge, ten years ago, there was no laboratory in France specialize in microwave and radiofrequencies characterization of H.T.S films. At this time, some microwave Laboratories have adapted to superconductors their existing means of measurement and other ones have developed original characterization techniques. As a whole, we distinguish the techniques applied to as-deposited HTS films and to processed films. In the oral presentation we will give the names of the Laboratories and groups which have developed these techniques and we will described briefly the following ones.

1) Characterization of as - deposited films :

- In RF : non contactless inductive measurement in order to obtain information on superconductive properties (critical temperature T_c, critical current J_c).
- In microwaves : in order to determine the surface impedance Z_s and the penetration depth λ of the electromagnetic waves.

  * Transmission measurements : in waveguides and free space
  * Resonant cavity measurements : in perturbation or by end-plate replacement
  * Dielectric resonator measurements

2) Characterization of etched films : usually in microwaves from the measurement of S_{ij} parameters of lines or resonators to determine Z_s and λ.

  * Measurements on wafer with coplanar probes
  * Measurements with the component in a package : normal or inverted microstrip techniques.

A Microwave Technique for the Broadband Determination of the Complex Permeability Tensor Components of Magnetized Ferrite

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The electromagnetic properties of magnetized ferrimagnetic materials at microwave frequencies are at the root of many applications such as circulators, phase shifters, attenuators and insulators. The implementation of such devices calls for an experimental determination of the electromagnetic characteristics of constituent materials.

When a static magnetic field is applied to a ferrite the permeability becomes tensorial and takes the following form in the Cartesian coordinate system :

$$\tilde{\mu}^* = \begin{pmatrix} \mu & j\kappa & 0 \\ -j\kappa & \mu & 0 \\ 0 & 0 & \mu_z \end{pmatrix},$$

where the tensor components $\mu = \mu' - j\mu''$, $\kappa = \kappa' - j\kappa''$ and $\mu_z = \mu_z' - j\mu_z''$ are complex to reveal the existence of magnetic losses.

Until now resonant cavities containing ferrite samples were used for measuring μ, κ and μ_z. In spite of their accuracy the resonant methods do not allow us to characterize materials in a wide frequency range since only a few frequency values can be exploited with different resonant systems.

A broad band measurement technique is presented to determine the complex permeability tensor components and the complex scalar permittivity $\varepsilon^* = \varepsilon' - j\varepsilon''$ of partly magnetized ferrites in a single experimental phase. The ferrite sample that is to be characterized is loaded in a rectangular waveguide. The guide is set in between the poles of an electromagnet to magnetize the sample. The measurable parameters are the reflection and transmission coefficients (S parameters) of the waveguide given by a network analyzer in a wide frequency range. The processing of the experimental data requires the calculation of the S parameters of the cell as a function of the electromagnetic characteristics of the ferrite (direct problem) and the use of an optimization procedure to match the measured and calculated S parameters (inverse problem).

At first the conditions leading to the nonreciprocity of the cell ($S_{11} \neq S_{22}$ and $S_{21} \neq S_{12}$) in order to obtain the same number of measurable parameters as for the characteristics we want to determine will be specified. The description of the calculation of the S parameters using the mode matching method at the cell discontinuities will be given. A comparison between theoretical and experimental values of the S parameters for ferrites of well-known properties will be done in the X-band (8-12 GHz) for the validation of the direct problem. We will bring to the fore the difficulties linked to the resolution of the inverse problem since the S parameters of the cell are non-linear functions of the ε', ε'', μ', μ'', κ', κ'' variables and many unknowns have to be determined. We will present specific optimization procedures that permit to avoid the divergence of the calculations or the convergence towards local minima of the objective function.

Microwave Material Characterization Using Focused Systems

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The increasing use of composite materials in the industry, and particularly in aeronautics, associated with the development of new Radar concepts induced a growing need of material characterization in the microwave range. The complex dielectric permittivity e^*, and magnetic permeability m^*, are required to design elements like absorbing coatings, radomes, or printed antennas from several GHz up to 100 Ghz.

After the development of theoretical models describing the electromagnetic behaviour of these materials in terms of e^* and m^*, it became quickly essential to bring experimental validations by measuring relevant parameters, as reflection and /or transmission coefficients, or resonant frequency and quality factor. Accessing other properties like the polarization modification, appeared to be interesting. Initially designed as laboratory setups, some systems were extended for automatic industrial use, as production control.

The two main principles developed for material characterization in these frequency bands consist in measuring the parameters of :

- A partially or fully loaded transmission line (microstrip, metallic waveguide, coaxial, dielectric resonator, ...). It requires a high precision machined sample in a very compact measurement cell. The operating frequency range is limited, up to the Ka band.
- The propagation through a sample using free space illumination (anechoïc chamber, focused systems, ...). In these conditions, the parallel plate sample is supposed to be illuminated by a plane wave or a Gaussian beam. Its size has to be large enough to reduce or avoid edge diffraction, otherwise it must be included in the theoretical model. Moreover, an anechoïc chamber is required to reduce perturbations due to the environment. Focusing the electromagnetic wave using ellipsoidal antennas or dielectric lenses is found to be a satisfactory solution.

In this paper are presented the different free space focused systems for material characterization developed in the authors' laboratory.

•*Characterization by transmission and reflection coefficients measurement :* it consists in two ellipsoidal antennas, illuminated by a primary horn placed at the closer focus. The second focus is common for both antennas and the sample place. Three different setups have been realized to cover the 6-28.5 GHz, 28.5-50 GHz, and 90-110 GHz frequency bands. The theoretical model is based on plane wave approximation, on a parallel plate.

•*Open resonator :* it consists in two spherical mirrors. A compromise had to be found between the operating frequency band (8-18 GHz, extended to 35 GHz), and the empty quality factor on the whole range, better than 30 000. The theoretical model uses continuity equations on the mirrors and the parallel plate sample, in the Gaussian beam formalism.

•*Non destructive testing :* an FM-CW radar is connected to an ellipsoidal antenna. An image of the reflected signal is provided by sweeping the antenna over the sample surface using a 2D actuator. This image can be investigated for default detection as inhomogeneity, impurities, humidity,

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Electromagnetic Characterization of Heterogeneous Chiral Material Using a Free-Space Compact Range System

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Since some years, a significant number of theoretical studies on complex materials have been developed. These materials are usually heterogeneous and they are generally produced to obtain some very specific properties for a given application.

Our paper is dedicated to special bi-isotropic heterogeneous materials named chiral materials. They are obtained by mixing in an isotropic way, chiral structures in a dielectric or magnetic host medium with or without loss. The chiral shape of inclusions is going to give special properties to the final material. The purpose of this study is to characterize these properties with measurements on a free space bench in the 4-18 GHz range.

The measurement system is composed of a HP8510C vectorial network analyzer and of reflectors of elliptic shape that focus the beam on the sample under study. We first present the bench of measurements, its properties and its limitations.

We introduce the different kinds of measurements realized on samples of heterogeneous chiral materials. These experiments are intended to characterize the properties of reflection, and transmission under normal or oblique incidence, the electromagnetic parameters of materials as well as some special physical properties. The whole of these measurements is intended to validate the theoretical representations of these materials in the microwave domain.

Non Destructive Testing of Radar Absorbing Materials for Industrial Production Stealthy Missiles

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This paper describes final results on the study of non destructive measurement methods of missiles in terms of stealthiness.

Measurements performed on full scale missiles allow to determine the reflectivity of the material and give estimation of its real RCS with regard to its nominal RCS. Different measurement techniques are rewieved, based on the use of coaxial transmission line, circular waveguide and spot focusing horn lens antenna.

Modeling design and characterization of spot focusing corrugated hors lens antennas operating in the frequency range 2-18 Ghz are presented. Finally, system configuration of full scale missile RCS measurements currently being utilized for production control is presented.

Keywords: Facility descriptions; RCS measurements

The Determination of Surface Resistance for Microwave Antennas Using Dielectric Resonator Cavity Techniques

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A method has been developed that now allows direct measurement of AC conductor losses for conducting surfaces in microwave antenna constructions. The AC conductor losses are measured both directly and from the construction of an actual antenna. Excellent agreement has been obtained between the two independent determinations. The electrical conductivity has been measured with a high Q, TE_{01n} mode, axial mode resonant cavity constructed both at 10 GHZ and 20 GHZ. The electrical conductivity has also been measured with a Parallel Plate Resonator using single crystal sapphire, single crystal quartz, and other Dielectric Resonators. The relation of conductor losses to antenna efficiency becomes increasingly important when considering alternatives to the more commonly used low resistance materials such as copper. In the Courtney configuration at microwave frequencies a relationship has been derived for surface resistance in terms of measured Q factors and geometric coefficients by solving the appropriate modal geometry for the cylindrical boundary value problem at hand. Surface Resistance measurements have been made for low Rs values such as those for copper, aluminum, and silver, in the range of 25-35mΩ. High surface resistance measurements up to 30Ω have also been performed.

A series of standard antenna tests were performed on an approximately 26.4cm long rod antenna. The combination rod antenna and ground plane were placed in an anechoic chamber. Swept gain measurements were performed using the standard insertion technique where the signal levels from the rod antenna and a known gain antenna were compared. The return loss versus frequency was also measured for the rod antenna. A series of computer simulations were performed in an attempt to replicate the measured data and assess some of the characteristics of the rod material. The simulations were performed using commercially available software that employs the Numerical Electromagnetics Code (NEC) as the calculating engine. The experimental results have indicated excellent agreement between the directly measured conductivities (cavity methods) and those conductivities derived from the computer simulations of the antenna data.

How Wide Frequency Band Dielectric Spectroscopy Contributes to Explain Chemical Reactions Under Microwaves

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I. Experimental procedure [1]

The measurement cell is a circular waveguide ended with a short-circuit. The sample to be characterized partially fills the cell and is surrounded with a Teflon annulus. Using an electromechanical switching system, the cell in an abrupt transition with a coaxial cable is alternatively connected to a network analyzer (probe), measuring admittance in the coaxial-to-circular transition plane (from 1 MHz to 1.8 GHz), and to a 2.45 GHz continuous power generator (up to 50W, pump), simultaneously heating the sample and measuring incident and reflected power using a bi-directional coupler. The sample complex dielectric constant is computed for each frequency, from the admittance value. This aperiodic instrumentation allows measurements with 434 MHz or 215 MHz variable power source (100W).

II. Studied reactions, dielectric analysis

Two kinds of chemical reactions under microwaves have been considered :
- Reticulation of an epoxy resin (DGEBA+DDS) [2]
- Saponification of an ester (octyl benzoate)

The two main origins of dielectric losses in a material are dipolar relaxation and conductivity by ionic particles. In the case of epoxy resin, since there are few ionic particles present in the system, losses are mainly due to dielectric relaxations. Thus, the evolution of relaxation frequency has been chosen as the control parameter for the reaction advancement. Moreover, in the case of ester saponification, even if both phenomena coexist, the ionic particle conductivity, which is the predominant phenomenon, is more convenient to get information about the reaction progress.

III. Results and discussion

The evolution of the dielectric parameters shows several differences between conventional and microwave heatings. Amplitudes and evolution rates of complex permittivities are different from one method to the other for a given medium, and even the yields are different. In the case of reticulation, we present the evolution of dipole relaxation frequencies as "dipolar temperatures" which are function of the evolution of the microwave (pump) electrical field (finite element simulation) in the sample. Similarly, in the case of saponification, we show how conductivity leads to temperature, which varies versus the microwave (pump) electrical field. These results, related to the ionic concentration of particles in the medium, allow us to qualitatively associate the evolution steps of permittivities with chemical reaction advancement.

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Current Density Measurements in Space Plasmas

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Current density is the only parameter in space plasmas that is not till now directly measured in space plasmas. There are several implicit methods mostly based on the principle of the gradiometer to get the information about this parameter by means of the estimate of the rotor of the **B** - field.

We propose the direct method of measurements of current density variations making use of a classic coil wounded around a high permeability magnetic toroid core, called a Rogowski's coil. The major difference with the classical use of such an instrument (as in differential cutout) is that in our case there is no wire to guide the particles and that we need a greater sensitivity. As a consequence the surface used should be greater (30 cm in diameter). All the particles that flow through the torus surface that carry the current are taken into account.

After having modeled this sensor and the sources of the possible noise, we have realized several prototypes. We carried out some tests by simulating the variations of current density using a wire passing through the coil. This idealized case allow us to measure the transfer function of the device and its sensitivity (the noise level as well as electromagnetic perturbations). Those experiments allow us to come to the conclusion that such a low sensitivity as $1\mu A/m^2.Hz^{1/2}$ (at 1 Hz) can be obtained and we have estimated the shielding that is required.

The next step is to validate the principle of measurements: that is to apply a known variable current in a plasma tank with the goal to be sure that different effects will not prevent current carrying particles to go through the torus of a fixed diameter. Because of signal level and perturbations, the greater is the torus diameter, the better are the results. But as long as realization is concern, slim big torus isn't easy. Spatial applications impose rather rigorous constraints, that's why it is necessary to have something robust and light.

The future of this sensor is a flight on a Ukrainian satellite.